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PETROLOGIC RESULTS OF A STUDY OF THE MINERALS FROM THE TERTIARY VOLCANIC ROCKS OF THE SAN JUAN REGION, COLORADO¹

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1. GEOLOGIC SETTING

BY ESPER S. LARSEN

This paper gives only a brief statement of those features of the Tertiary volcanic rocks of the San Juan region that bear rather directly on the mineralogic problem under discussion. For additional information the reader is referred to the recent bulletin of Cross and Larsen.²

The Tertiary volcanic rocks overlies rocks that range in age from pre-Cambrian to Oligocene, and the volcanic rocks themselves range in age from Miocene to Quaternary. They form a great pile that is about 100 miles across and that exceeds 5,000 feet in thickness over much of this area. They have been studied in some detail and have been mapped as stratigraphic units within the San Juan area. The generalized section that follows omits some smaller units and subdivisions not essential to the problems of this series of papers.

Quaternary andesite. A single small body.

Erosion to mountain topography.

Pliocene (?):

Hinsdale volcanic series:

Andesite. Local domes, mostly in New Mexico.

Andesite-basalt. Mostly flows.

Rhyolite. Flows and tuffs.

Los Pinos. Breccias with some flows. Latite-andesite.

Erosion to peneplain.

Miocene (?):

Fisher latite-andesite.

Erosion to mountain topography.

Miocene:

Potosi volcanic series:

Piedra rhyolite.

Erosion to mountain topography.

¹ Published with permission of the Director of the U. S. Geological Survey.

² Cross, Whitman, and Larsen, E. S., A brief review of the geology of the San Juan region of southwestern Colorado: *U. S. Geol. Survey, Bull.* **843**, 1935.

Huerto andesite.

Alboroto quartz latite.

Erosion to mountain topography.

Sheep Mountain andesite.

Treasure Mountain quartz latite.

Erosion to mountain topography.

Conejos andesite.

Erosion to a mountain topography.

Silverton volcanic series with several subdivisions.

Erosion to mountain topography.

San Juan tuff.

Erosion.

Lake Fork andesite.

The rocks older than the Potosi occupy a relatively small area, chiefly in the western part of the region, and they are in general too much altered for a detailed study of their minerals. The rocks of the Potosi series are the most widespread. They had a total estimated volume of 5,600 cubic miles and are composed of about equal proportions of rhyolites (including quartz latites) and andesitic rocks. The Fisher and Hinsdale rocks are widespread but had a much smaller volume than the Potosi rocks.

Each of the subdivisions of the Potosi is made up of many flows and clastic layers. The three rhyolite and quartz latite members are made up largely of regularly layered flows and tuff beds that spread over very large areas. Few centers for their eruption have been found. The rocks of all three of these members vary considerably in texture and composition, but are chiefly rhyolites and quartz latites, with a few local thin andesite layers. The two younger andesitic members (Sheep Mountain and Huerto) are more local in occurrence and chaotic in structure than the rhyolitic members, and are piled up about local centers. The Conejos andesite is a thick widespread formation. The andesite members also vary considerably in composition and texture and carry local bodies of quartz latite or even rhyolite.

The Fisher rocks were piled up about several volcanic centers. They range from quartz latite (not far from rhyolite) to pyroxene andesite, or rarely to basalt. As a group, they are characterized by large phenocrysts. These phenocrysts are plagioclase, hornblende, and pyroxene in the andesites; these same minerals together with biotite in the quartz latites; and orthoclase, plagioclase, and biotite, with or without hornblende and quartz, in the rhyolitic rocks.

The Hinsdale members occur in rather scattered, relatively thin bodies and were extruded from a number of centers. The andesite makes up a group of volcanic domes in northern New Mexico, south of the San Luis Valley, and ranges from cristobalite latite to basalt. The Hinsdale ande-

site-basalts occur in thin widespread flows that resemble plateau basalt on a small scale. They are basalts in the southern part of the area but are olivine and quartz-olivine andesites and basalts in the northern part.

The San Juan area is probably the largest body of volcanic rocks that has yet been studied in detail. It is well exposed in deep canyons and is therefore favorable for a study such as the present one. In the course of the study and mapping, many thousands of specimens were collected and sectioned, and more than 100 analyses of rocks were made, chiefly in the laboratory of the United States Geological Survey. These analyses were carefully selected to represent the various rocks in the mapped units. Twenty-three analyses of minerals separated from the rocks have been made by Mr. F. A. Gonyer, of the Department of Mineralogy and Petrography at Harvard University.

These volcanic rocks represent an excellent petrographic province, and the same types, chemically and in large part texturally and mineralogically, recur again and again. Variation diagrams of the rocks—plotted against $\frac{1}{3}\text{SiO}_2 + \text{K}_2\text{O} - \text{FeO}$ (total iron) — $\text{MgO} - \text{CaO}$ to place the rocks quantitatively between basalt and rhyolite—show surprisingly regular curves and the eleven major formations fit essentially the same variation diagram.

Taking everything into consideration, the San Juan region offers an unusually favorable opportunity for the study of the petrologic significance of the minerals of a series of volcanic rocks of the ordinary lime-alkali series.

Lavas are favorable for a study of the crystallization of igneous rocks because they afford a series of naturally chilled rocks that are somewhat similar to those formed experimentally by quenching in the laboratory.

2. THE SILICA MINERALS

BY ESPER S. LARSEN

The San Juan lavas offer a favorable opportunity for a study of the silica minerals, for all three forms—quartz, tridymite, and cristobalite—are common in these lavas, and the rocks have been studied with some care in order to identify these minerals.

RELATIVE ABUNDANCE OF QUARTZ, TRIDYMITE, AND CRISTOBALITE

Tridymite has commonly been considered to be a rather rare mineral, but in the San Juan lavas it is present in somewhat greater amount than quartz. It makes up as much as one-fourth or more of some of the rocks. It is estimated to be the third mineral in abundance in the San Juan lavas as a whole, and is exceeded in amount only by feldspar and pyroxene. An estimate of the quantity of tridymite in the San Juan lavas

is 350 cubic miles, or enough to cover the State of Massachusetts with a uniform layer 250 feet thick. The quantity of quartz is nearly as great as that of tridymite.

Cristobalite that can be determined with the microscope is a fairly widespread mineral in the lavas, but it very rarely makes up more than a small fraction of 1 per cent of any lava. Cristobalite, as determined by x-ray methods by Dr. C. S. Hurlbut,³ is the chief silica mineral of the spherulites and submicroscopic parts of the rhyolitic rocks, and such cristobalite is nearly as abundant as tridymite.

In other younger lavas of the western United States I have found tridymite and cristobalite about as abundant and widespread as in the San Juan region, and specimens of such lavas from other parts of the world seem to show a similar amount. It seems, therefore, that tridymite is a rather common and abundant mineral in young lavas and that it should be given more emphasis in our textbooks on mineralogy and petrology, and in the literature in general. Cristobalite has been considered a very rare mineral—a mineral curiosity—but in the San Juan region, as shown by the microscope, it is present in small amount in about a tenth of the lavas. It is equally common in fresh lavas that I have seen from other localities.

QUARTZ

Quartz is present in the granular intrusive rocks, as phenocrysts in the lavas, and in the groundmass. It is the only silica mineral in the intrusive rocks, except those which were intruded very near the surface.

Quartz phenocrysts are relatively scarce in the San Juan volcanic rocks; they are present in nearly as large a proportion of the basaltic lavas as of the quartz latite and rhyolite lavas. They are rare in the andesites. The quartz phenocrysts in the basalts, although conspicuous, never make up more than 2 per cent of the rock. Almost all of them are associated with olivine phenocrysts, and they are invariably much resorbed and have a narrow reaction rim of small augite rods. A photomicrograph of a typical quartz phenocryst is shown in Fig. 1. The resorption may be complete and leave only the reaction rim of augite rods. The quartz basalts described by Iddings⁴ from the Tewan Mountains, New Mexico, are from the southern extension of the San Juan volcanic province. The name Tewan Mountains cannot be found on any map of New Mexico that I have seen, but Iddings' description shows clearly

³ Hurlbut, C. S., x-ray determination of the silica minerals in submicroscopic intergrowths: *Am. Mineral.*, vol. 21, pp. 727-730, 1936.

⁴ Iddings, J. P., On a group of volcanic rocks from the Tewan Mountains, N. Mex., and on the occurrence of primary quartz in certain basalts: *U. S. Geol. Survey, Bull.* 66, 1890.

that his rocks came from the Valles Mountains and White Rock Canyon, west of Santa Fe.

The quartz phenocrysts are most commonly 1 to 2 millimeters across. They have all the appearance of typical phenocrysts, but there has always been doubt as to their origin. If they represent partly resorbed inclusions from a sandstone or older igneous rock, no remnants of the inclusions were found, and none of the other minerals that should have been associated with the quartz are present. Their distribution in any given flow appears to be uniform. The magma must therefore have been

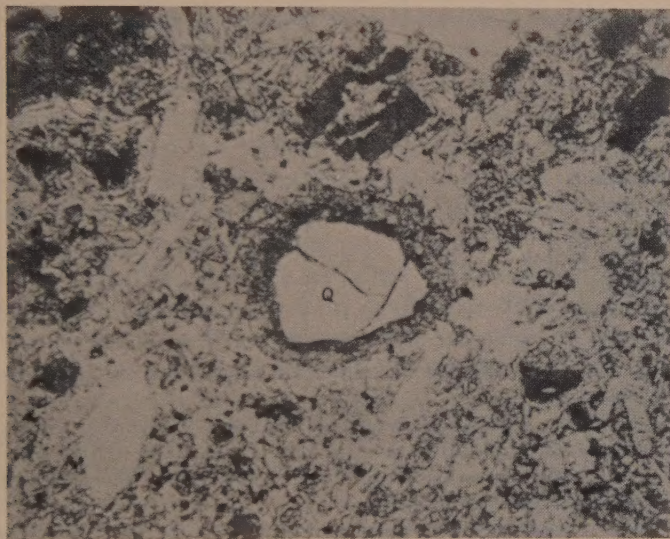


FIG. 1. Quartz phenocryst in a basalt from Valles Mountains, New Mexico, J. L. 23. Shows the characteristic corona of small augite rods. Enlarged 31 diameters.

thoroughly mixed and everything reworked but the quartz, after the inclusions were added and before eruption. The quartz must have been slow to go into solution. Quartz phenocrysts were found in no basalt that did not show quartz in the norm, and some of the quartz-olivine rocks have 6.9 per cent of quartz in the norm. Other rocks in the San Juan area that carry phenocrysts of olivine, but none of quartz, have as much as 12.7 per cent of quartz in the norm, and the groundmass alone may have as much as 17.4 per cent. Many olivine rocks have more than 8 per cent of quartz in the norm. Some of these rocks have determinable quartz and orthoclase in the groundmass. Properly most of these rocks should be called olivine or quartz-olivine andesites. Rocks with quartz pheno-

crysts not uncommonly have cristobalite in the gas cavities. When plotted on the variation diagram with the other rocks, the quartz basalts do not fit the variation diagram as well as do the other rocks, though some of them fit very well. A few are 2 per cent high in SiO_2 , many are very low in FeO , and some are high in MgO . Table 1 gives some of the significant characters of six quartz basalts from the San Juan province.

TABLE 1.—PHENOCRYSTS AND NORMATIVE QUARTZ IN QUARTZ
BASALTS FROM THE SAN JUAN PROVINCE
(in percentages)

Rock	NM 421	J 117	NM 213	Up 23	Sc 1206	Up 24
Phenocrysts:						
Quartz.....	$\frac{1}{2}$	2	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
Olivine.....	$\frac{1}{2}$	3	7	5	3	$\frac{1}{2}$
Diopside.....	$\frac{1}{2}$	...	1	$\frac{1}{2}$	2	1
Hypersthene.....	1	...	...	...	...	...
Plagioclase.....	$1\frac{1}{2}$	5	2	1	2	3
Sanidine.....	...	...	...	...	...	...
Quartz in norm of rock.	5.8	5.6	6.9	3.4	4.5	3.5
Quartz in norm of groundmass.....	6.1	5.7	7.8	5.3	5.4	...

NM 421. Lava from Hinsdale andesite dome called Cerro Aire, 4 miles east of No. Agua, N. Mex.

* J 117. Lava from Santa Clara Canyon, 14 miles west of Espanola, N. Mex. The feldspar phenocrysts have a rounded, resorbed core of An_{46} and a sharply separated outer shell of An_{63} . The cores must be foreign to the magma. Small olivine crystals make up 5 per cent of the groundmass. An unusual rock.

NM 213. Lava of Ortez Peak, 3 miles south of Tres Piedras, N. Mex. A rather extreme type of quartz basalt.

Up 23. Hinsdale andesite-basalt from Cannibal Plateau, east of Lake City, Colo. The groundmass is 1.2 per cent low in MgO .

Sc 1206. Hinsdale andesite-basalt from area northeast of the mouth of Lost Trail Creek, near center of San Cristobal quadrangle, Colorado. Upper flow.

Up 24. Hinsdale andesite-basalt from Cannibal Plateau, east of Lake City, Colo. An unusual rock.

The olivine in the quartz basalts is about like the olivine in the rocks without quartz, and contains about 25 to 30 per cent of fayalite. (See the data on olivine, published later.) There is no reason to think that the quartz and olivine did not crystallize from the basaltic magma, except the experimental fact that in the simpler system, MgO-FeO-SiO_2 , quartz and olivine are not in equilibrium.⁵

⁵ Bowen, N. L., and Schairer, J. F., The system MgO-FeO-SiO_2 : *Am. Jour. Sci.*, 5th ser., vol. 29, pp. 151-217, especially pp. 214-215, 1935.

The equilibrium diagram of Bowen and Schairer for this system is of the utmost value to petrographers, and its usefulness will increase in years to come. However, I do not believe that we should draw too close an analogy between the crystallization of natural rocks and that shown in the equilibrium diagrams. The artificial system is much simpler than that of the natural basalts, which have at least nine essential components. Pressure also displaces the equilibrium. This complexity in the system reduces the temperature of crystallization of olivine—of the composition of the olivines in the quartz basalts—from a range between $1,500^{\circ}$ and $1,600^{\circ}\text{C.}$ in the system MgO-FeO-SiO_2 to less than 900° in the quartz basalt. According to the equilibrium diagram, the olivines of basalts would be in equilibrium with a liquid that had just about enough SiO_2 to form pyroxene. In the San Juan rocks olivine is found in rocks that contain as much as 12.7 per cent excess of SiO_2 above saturation, and with rocks whose groundmass contains as much as 17.4 per cent excess of SiO_2 . All the "quartz basalts" analyzed for us contained quartz in the norm, but some described by Iddings show a few per cent of olivine in the norm. On the diagram for MgO-FeO-SiO_2 an excess of silica such as is common in quartz basalts would place the rock far from the olivine field and well in the field in which free silica would crystallize. I can see no justification for concluding from the equilibrium diagram that quartz in basalts must be foreign to the magma. The petrologic evidence points strongly to the conclusion that the quartz crystallized from the basalt magma as well as did the olivine. In fact, from analogy with the artificial system we might expect quartz but not olivine to crystallize from a magma of the composition of a quartz basalt.

Quartz phenocrysts are rare in the olivine-free andesites and where present they show the resorption and augite coronas characteristic of the quartz phenocrysts of the basalts.

Quartz phenocrysts are more common in the quartz latites than in any of the other rocks, but probably less than half even of the quartz latites carry such phenocrysts. They are never present in excess of 5 per cent of the rock. The great flows and tuffs of Alboroto quartz latite characteristically carry quartz phenocrysts, as do most of the quartz latites of the Piedra, but they are never present in the Treasure Mountain quartz latites, although these three quartz latites cover the same range in composition and show no appreciable difference in bulk composition. All the quartz latites carry phenocrysts of biotite and plagioclase; those with quartz phenocrysts carry in addition phenocrysts of orthoclase, hornblende, and titanite, with or without augite, whereas those without quartz phenocrysts carry only augite phenocrysts in addition to those of biotite and plagioclase. In the Alboroto rocks, which contain quartz

and orthoclase, the plagioclase is more sodic than in the Treasure Mountain rocks, which lack these phenocrysts, but in the Piedra rocks the plagioclase phenocrysts are about like those of the Treasure Mountain rocks. The simplest explanation for this condition would be that crystallization had proceeded farther in the rocks with quartz and orthoclase phenocrysts than in those that lack these phenocrysts, but a comparison of the groundmasses of the two types shows that in both types the groundmass varies considerably in composition and over the same range. We are forced to the conclusion that some of the "intangibles," such as pressure or mineralizers, determine the intratelluric crystallization of the quartz, orthoclase, hornblende, and titanite in the one group and augite in the other. In confirmation of this conclusion, the quartz, orthoclase, and hornblende all show more or less resorption, which suggests that crystallization at greater depth favors their formation.

Quartz phenocrysts are less common in the rhyolites than in the quartz latites. They are present to the extent of a few per cent in the Hinsdale rhyolite, but this rhyolite is of small extent and thickness. They are present in amounts up to 15 per cent in the Sunshine Peak rhyolite, a local body of rhyolite in the northwestern part of the San Cristobal quadrangle. They are rare in the extensive rhyolites of the Potosi series but are found in some small dikes and other intrusive rocks of Potosi age.

Quartz is the chief silica mineral in the groundmass of the andesites and andesite-latites. It commonly occurs in a very fine spongelike intergrowth with alkali feldspar, which extinguishes in relatively large areas and contains minute tablets of plagioclase and grains of iron ore. As this intergrowth increases in coarseness it becomes a typical micrographic intergrowth. In the groundmass of the rhyolites and quartz latites quartz is less common than tridymite and cristobalite. These groundmasses nearly all tend to be fine fibrous intergrowths, either in spherulites or in less regular forms. Quartz is only occasionally the silica mineral in these growths. An interesting form of quartz in the rhyolites from the Creede area has been described and figured by Emmons and Larsen.⁶ The rock is fluidal, and much of it is reddish brown and dense, with nearly white, porous streaks, roughly ellipsoidal in shape and of the order of magnitude of 200 by 20 by 2 millimeters. Under the microscope the dense part is holocrystalline but so finely crystalline that it might be mistaken for glass, whereas the light porous parts are rather coarsely crystalline and are made up of quartz and alkali feldspar. The feldspar is in good crystals and is concentrated near the borders, but the quartz

⁶ Emmons, W. H., and Larsen, E. S., *Geology and ore deposits of the Creede district, Colo.: U. S. Geol. Survey, Bull. 718*, pp. 18-24 and pls. 5, 6, 7, 1923.

is concentrated near the more porous central parts. These streaks grade into less regular streaks. They clearly represent rounded patches or bubbles, rich in mineralizers, which formed just before the last movement of the rock and have been drawn out by flow; they are probably the last part of the rock to crystallize. They might be considered as analogous to the pegmatitic patches in granite.

A groundmass made up of microgranular quartz and feldspar is very rare in the San Juan lavas.

TRIDYMITITE

Tridymite is less common than cristobalite in the basalts, but in a few basalts a friable material that partly fills the gas cavities is made up

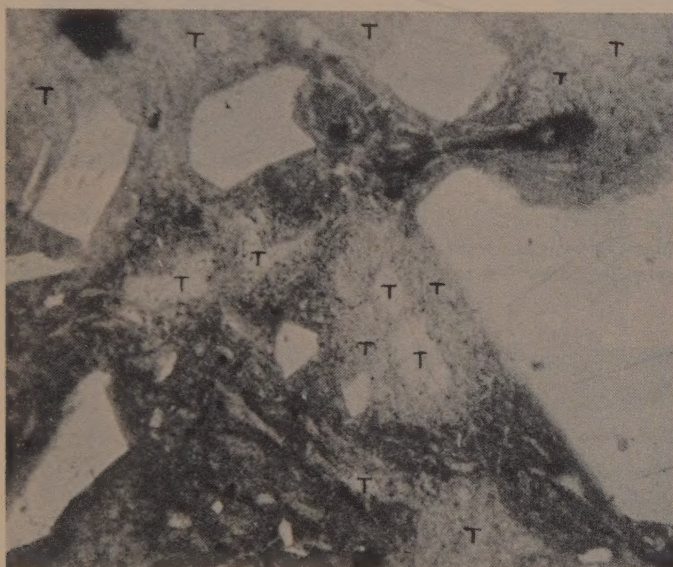


FIG. 2. Thin section in ordinary light of tridymite latite from Piedra flow of Bulldog Mountain, west of Creede, Colo. (Lag. 48). Relatively coarsely crystalline feldspar and tridymite (T) in the porous parts of the rock, and submicroscopic feldspar and cristobalite (?) in the dense parts. Enlarged 31 diameters.

chiefly of tridymite together with some albite and pale biotite, and rarely needles of hornblende and prisms of zircon.

In the rhyolites and quartz latites tridymite is the chief silica mineral. It is confined to the groundmass and is especially common in the more porous, coarsely crystalline parts of the groundmass that were richer in mineralizers and that crystallized last. Figures 2 and 3 show thin sections of typical tridymite rhyolite and latite, and Fig. 4 shows a thin



FIG. 3. Thin section in ordinary light of tridymite rhyolite from the Alboroto flow of Pine Creek Mesa, along road 3 miles S. 30° W. of Sapinero, Colo. (Up. 3027). Tridymite (T) concentrated in the coarser, more porous parts of the groundmass. Enlarged 31 diameters.

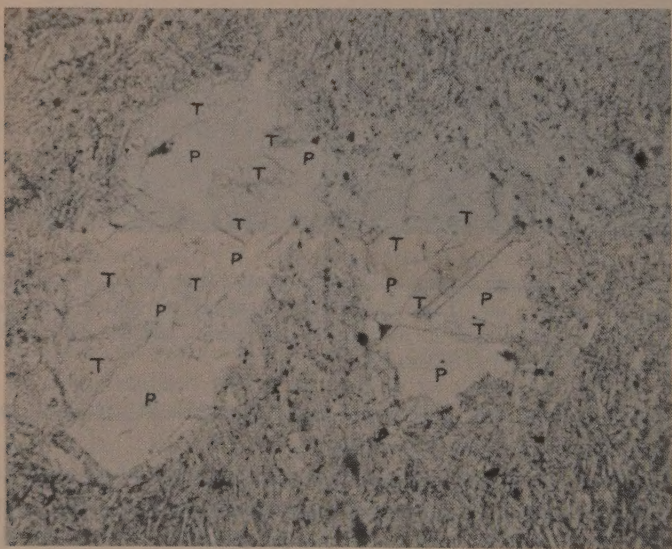


FIG. 4. Thin section in ordinary light showing coarse tridymite (T) in the porous (P) layers of a latite of pre-Potosi age (*D.N. g.*). From Red Rock Creek, 2½ miles above valley in northeastern part of Del Norte quadrangle, Colorado. Enlarged 31 diameters.

section of a latite with unusually coarse tridymite plates that can be easily seen in the hand specimen. Many rocks contain 25 per cent of tridymite. In the andesites tridymite is rather uncommon.

Tridymite is an abundant mineral in some of the rhyolitic tuffs, where it in part forms the binder for the tuff and was formed after the tuff was deposited. Such tuffs were no doubt deposited while they were still hot and contained abundant mineralizers. Some of these tuffs have much the appearance of lava flows, and they grade into eutaxitic rhyolites.

Rhyolites with quartz phenocrysts carry much tridymite in the groundmass as commonly as do those without such phenocrysts. I have never seen the slightest tendency for the quartz to be inverted to tridymite or replaced by it.

CRISTOBALITE

Cristobalite was microscopically identified in the San Juan lavas only as rounded spherulites or crystals perched on the walls of the larger gas

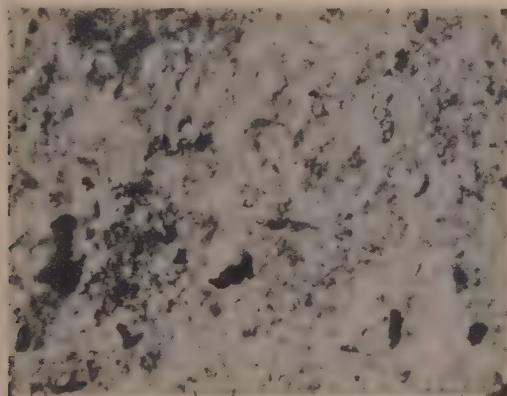


FIG. 5. Cristobalite spherulites (white) on the walls of vesicles in an andesite from the ridge west of the mouth of Hot Spring Creek, Jemez quadrangle, New Mexico. Photograph of part of a hand specimen. Enlarged 2 diameters.

cavities. In most specimens they are sparsely scattered on the cavity walls, but in some they are closely spaced. They are commonly less than a millimeter across, but in some lavas they reach a diameter of a little more than a millimeter. They are less well formed but are otherwise very similar to crystals of cristobalite deposited by steam on the surface of tubes of silica glass and described and figured by Greig, Merwin, and Shepherd.⁷

⁷ Greig, J. W., Merwin, H. E., and Shepherd, E. S., Notes on the volatile transport of silica: *Am. Jour. Sci.*, 5th ser., vol. 25, pp. 61-73, 1933.

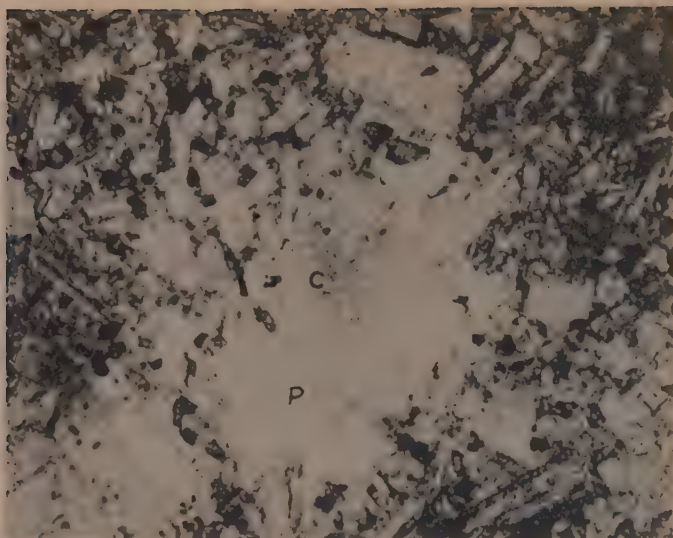


FIG. 6. Thin section in ordinary light of cristobalite (C) in the vesicles (P) of an andesite from Antone Peak, New Mexico. Enlarged 62 diameters.

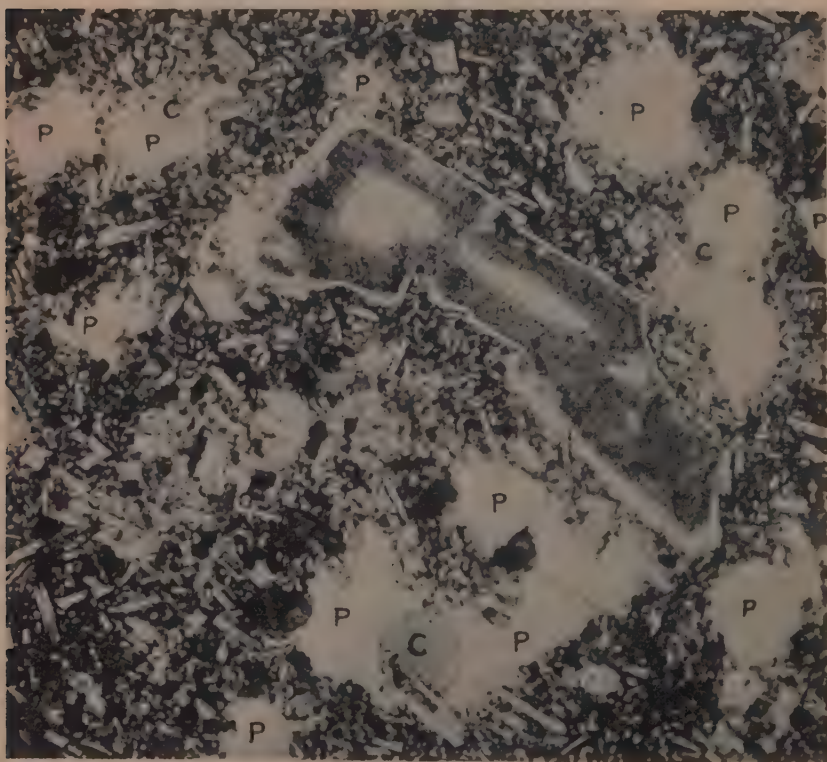


FIG. 7. Same as Fig. 6. Enlarged 30 diameters. The cristobalite spherulite near the upper left corner is enlarged in Fig. 6.

Cristobalite is the most common silica mineral in the gas cavities of basaltic lavas, and is present in about a fourth of the basaltic lavas examined. It is less common in the andesites. It is very rare in gas cavities of the rhyolitic rocks, and in these rocks was found only on the walls of the cavities of large spherulites, especially where these spherulites are embedded in obsidian. Typical cristobalite spherulites are shown in hand specimen in Fig. 5 and in thin section in Figs. 6 and 7. Rogers found cristobalite to be the common silica mineral of spherulites, and x -ray studies by Dr. C. S. Hurlbut have confirmed this determination.⁸ Hurlbut found that the silica mineral of spherulites and similar submicroscopic intergrowths in the groundmasses of rhyolites from the San Juan region is cristobalite. In some of these spherulites the cristobalite is more or less concentrated in concentric rings or in rounded areas.

CONDITIONS OF FORMATION OF THE SILICA MINERALS

Quartz is the only silica mineral found in phenocrysts and in the granular rocks, where it must have crystallized slowly and under conditions favorable for equilibrium. We are therefore justified in believing that the quartz crystallized as a stable form and hence below the quartz-tridymite inversion temperature, which is 870°C. at a pressure of one atmosphere.⁹ At a pressure of 1,000 atmospheres, corresponding to a depth of nearly $2\frac{1}{2}$ miles, this inversion temperature is estimated to be increased to about 970°C.¹⁰

It is very probable that the quartz phenocrysts, even of the quartz basalts, were the stable form at the time the lava flows were extruded, because the liquid (groundmass) in which the quartz was embedded should have served as a flux to hasten equilibrium, as it contained several per cent of free silica and must have been a solvent for silica. This is also shown by the resorption of the quartz. The conclusion seems justified that the San Juan lavas were extruded at temperatures below about 900°C.

Both quartz and tridymite formed in the mineralizer-enriched parts of the groundmasses. No clue was found as to why quartz crystallized in the porous groundmass in one rock and tridymite in another, but tridymite is much the commoner of the two. Cristobalite is the characteristic mineral of the dense, submicroscopic parts of the groundmasses,

⁸ Rogers, A. F., Natural history of the silica minerals: *Am. Mineral.*, vol. 13, p. 82, 1928. Hurlbut, C. S., personal communication.

⁹ Fenner, C. N., The stability relations of the silica minerals: *Am. Jour. Sci.*, 4th ser., vol. 36, p. 383, 1913.

¹⁰ Bowen, N. L., Geologic thermometry, from Fairbank's Laboratory investigation of ores, p. 181, McGraw-Hill Book Co., 1928.

including the spherulites, and is confined to such groundmasses. Cristobalite is the chief silica mineral of the larger gas cavities, though tridymite and quartz are both found in such cavities. Tridymite clearly developed as an unstable form owing to rapid crystallization in the presence of mineralizers. Cristobalite developed as an unstable form during the relatively rapid crystallization of the viscous cotectic groundmass. Where crystallization is more free, quartz forms in the groundmass.

Rogers¹¹ states: "I doubt whether tridymite is ever even a late magmatic mineral . . . The tridymite-bearing streaks I would interpret as having been formed by pneumatolytic metamorphism." And again, "In my opinion tridymite is not a magmatic mineral, but a metamorphic one." I cannot agree with Rogers. In the San Juan area, and in many other places as well, tridymite is found in the freshest rocks and is in no way associated with altered rocks or with areas in which the rocks are altered. It is not confined to red or brown rocks, although most of the rhyolites and quartz latites are red, but is found as well in white or gray rocks. A red or brown color in lavas is not evidence of alteration but is commonly the color of the fresh rock and was formed during the crystallization of the rock. This is especially true of rhyolitic rocks.

The distribution of tridymite in the rocks and the study of the thin sections in no way suggests a secondary origin, although such evidence is not conclusive. Tridymite is characteristic of certain lava flows, many of which can be followed for tens of miles in the walls of canyons. In any particular flow both the quantity and distribution of the tridymite are uniform, so that a specimen or thin section of a flow taken at one locality is almost identical with others from the same flow 10 miles or more distant. Indeed, the particular rock to which Rogers refers in the first statement quoted from him came from a flow, or possibly a group of related flows, near Creede, Colo., that are nearly flat and a few hundred feet thick and that lie at a definite stratigraphic horizon in the section over an area nearly 30 miles across. Specimens from this horizon from any part of this area are all rich in tridymite and nearly identical in character. In this area some of the overlying and underlying layers may or may not have tridymite—some are tuffs, some are glassy, and some have quartz in the groundmass. The rocks are generally fresh, but locally, as near some of the mineralization near Creede, they are altered and quartz has replaced much of the rock.

In a series of superimposed flows one flow may have tridymite and a groundmass of a particular habit, another tridymite and a groundmass of a different habit, and still another may have a groundmass that con-

¹¹ Rogers, A. F., *Natural history of the silica minerals: Am. Mineral.*, vol. 13, pp. 80-81, 1928.

tains quartz. Many of the flows have a thin layer of fresh obsidian at the base throughout their extent and, rather sharply separated from this layer, a main part in which the groundmass is crystalline and carries as much as 20 to even 30 per cent of tridymite.

There seems little room for doubt that the tridymite crystallized after the lavas had practically ceased to flow, but during their original cooling and as a part of the crystallization of the groundmass of the rock. The tridymite tended to concentrate, as did the quartz, in the last residual, mineralizer-rich part of the magma. To a very small extent, tridymite was deposited in gas cavities during the cooling of the rock, but after the crystallization of the groundmass.

On hydrothermal or any other metamorphism the unstable form tridymite should be changed to the stable form quartz, unless the temperature was above the quartz-tridymite inversion temperature, a very rare condition under metamorphism. On the recrystallization of a glass or introduction of silica by steam or other gases, the unstable form might be deposited, as it might be less soluble than the silica of the glass or might be brought in from an environment—such as higher temperature—in which silica was more soluble.

Tridymite has been found in the gas cavities of a few basalts, where it clearly crystallized from a gas phase, but cristobalite is the common form in the large gas cavities. The two forms were rarely found in the same gas cavity. The tridymite fills a much greater part of the cavities, than does the cristobalite. The cristobalite, and probably the tridymite in these cavities probably formed by transport of silica by steam.¹²

Quartz may be found as phenocrysts in a rock and tridymite or cristobalite in the gas cavities or in the groundmass, but rarely have two forms been found to have crystallized together. In some rocks quartz is present as phenocrysts, tridymite in the porous parts of the groundmass, and cristobalite in the dense, submicroscopic parts of the groundmass.

To sum up the conditions under which the three forms of silica were crystallized in the San Juan area:

1. Quartz alone forms as phenocrysts in the granular rocks, in the intrusive rocks, or wherever crystallization was slow enough for equilibrium to be reached.
2. Tridymite, less commonly quartz, forms during the crystallization of the porous parts of the groundmass, the tridymite as an unstable form owing to rapid crystallization.
3. Cristobalite forms in the dense parts of the groundmass when crystallization is rapid or retarded and is not "lubricated" by mineralizers.

¹² Greig, J. W., Merwin, H. E., and Shepherd, E. S., *op. cit.*

4. Cristobalite, rarely tridymite or quartz, forms in the larger gas cavities by gas transfer after solidification of the groundmass, especially in the andesites and basalts.

INVERSIONS OF SILICA MINERALS

In the San Juan rocks the tridymite and cristobalite, though of Miocene age, show no trace of a change to quartz except in a very few places where they have been recrystallized by hydrothermal solutions that altered the whole rock. Moehlman¹³ has described paramorphs of quartz after both tridymite and cristobalite in altered rocks from the vicinity of Ouray, Colo., in the western part of the San Juan region. The freshness of the tridymite and cristobalite in the fresh rocks indicates that these minerals may persist indefinitely under favorable conditions. However, I have seen neither of them in rocks older than Tertiary. It is not surprising that these forms of silica, which are unstable under most conditions under which the rocks we see were formed, are not found in older rocks, for they would probably be replaced by quartz during even a very low degree of metamorphism or recrystallization. It will be interesting to record any finds of tridymite or cristobalite in older rocks. A similar observation in regard to old volcanic glasses would be interesting. True glass should be distinguished from material with submicroscopic crystallization. In my experience, true glass is definitely vitreous in appearance and not felsitic.

3. PYROXENES

BY ESPER S. LARSEN AND JOHN IRVING

GENERAL FEATURES

The pyroxenes are the most abundant mafic minerals of the San Juan extrusive rocks as a whole. They are associated with olivine in the basalts, are the only mafic silicates in most of the low-silica andesites, are present with biotite, with or without hornblende, in more than half of the quartz latites, and are present in small amount in some of the rhyolites. Monoclinic pyroxene, which probably approaches pigeonite in composition, is the only pyroxene in most of the basalts. In the andesites both hypersthene and diopside are commonly present, with diopside usually predominating. In the more siliceous rocks the pyroxene is nearly all diopside.

Hypersthene is rarely found in the same rock with olivine, except in the olivine andesites, and it is rare in rocks that contain less than 54 per cent of SiO_2 . It is present in most rocks that contain from 57 to 59

¹³ Moehlman, R. S., Quartz paramorphs after tridymite and cristobalite: *Am. Mineral.*, vol. 20, pp. 808-810, 1935.

per cent of SiO_2 ; with higher content of SiO_2 it is less common; and in rocks that contain more than 65 per cent of SiO_2 it is rare and present in very small amount.

In the basalts the clinopyroxene is mostly interstitial to the feldspar, or in the groundmass, and is rarely present as phenocrysts. In the andesites it is chiefly present as early phenocrysts but partly as small crystals in the groundmass. In the quartz latites and rhyolites it occurs almost exclusively as phenocrysts.

The hypersthene usually occurs in better-formed crystals than the augite. Hypersthene is to a large extent altered to bastite, whereas the clinopyroxene is commonly fresh. The pyroxenes in some of the rocks are irregularly colored reddish brown, probably from partial oxidation of the iron by gases. Diopside grows around hypersthene and probably partly replaces it in a few specimens.

Three analyses of diopsides from rocks of different composition and one of hypersthene have been made by F. A. Gonyer and are given, together with other data, in Table 2. None of the pyroxene of the basalts was suitable for analysis. All four pyroxenes show a deficiency of SiO_2 of 4 to 6 per cent for a metasilicate formula. The diopsides have about enough silica to form the maximum amount of acmite, diopside, and clinohypersthene, leaving little or none to be allotted to the Fe_2O_3 and Al_2O_3 . The diopsides have only moderate amounts of Fe_2O_3 and Al_2O_3 , but the hypersthene has a large amount of Fe_2O_3 . The diopsides from the

TABLE 2. ANALYSES AND OPTICAL PROPERTIES OF PYROXENES FROM THE SAN JUAN LAVAS

	1	2	3	4	5	6	7	8	9
SiO_2	51.05	51.45	50.74	51.58					
TiO_2	0.36	0.36	0.95	0.45					
Al_2O_3	1.80	1.50	2.98	1.70					
Fe_2O_3	2.03	3.15	2.37	3.15					
FeO	6.56	6.45	10.04	18.11					
MnO	1.22	0.53	0.17	0.39					
MgO	13.82	14.11	14.24	22.01					
CaO	22.06	21.69	17.88	1.82					
Na_2O	0.38	0.32	0.67						
K_2O	0.08	None							
$\text{H}_2\text{O}-$	0.04	None	0.03						
$\text{H}_2\text{O}+$	0.17	0.16	0.17	0.40					
P_2O_5	0.46	0.48							
F.....	Trace								
	100.03	100.20	100.24	99.61					

WEIGHT PER CENT OF CONVENTIONAL MOLECULES¹

NaFeSi ₂ O ₆ ...	3.2	2.3	5.1	...					
CaMgSi ₂ O ₆ ...	75.2	76.3	69.1	7.1					
CaFeSi ₂ O ₆ ...	5.5	3.7	...	...					
CaMnSi ₂ O ₆ ...	4.3	2.0	...	...					
MgSiO ₃	...	...	3.6	51.8					
FeSiO ₃	9.3	9.8	18.7	33.7					
Fe ₂ Si ₂ O ₉	...	1.6	...	2.5					
Fe ₂ O ₃	1.0	1.6	.6	1.9					
Al ₂ O ₃	1.8	1.5	3.0	1.7					
Deficiency of SiO ₂ for metasilicate	5.1	4.2	6.2	2.7					
MgO(mol.)	2.56	2.60	2.04	1.84					
2Fe ₂ O ₃ +FeO									
α	1.684	1.686	1.695	1.702	1.692	1.696	1.690	1.688	1.690
β	1.691	1.693	1.701	1.707		1.703	1.694	1.693	
γ	1.712	1.713	1.719	1.712	1.723	1.730	1.721	1.701	1.720
2V.....	60+	64	55		Rather small	Rather small	Medium		
γ/ϵ	41	40	41						
Specific gravity...	3.370	3.37	3.405	3.481					

¹ Small amount of MnSiO₃ included in FeSiO₃.

1. Diopside from phenocrysts of Treasure Mountain quartz latite (DN 3006) about 5 miles southeast of Del Norte, Colorado, north fork of Gulch between Lime and Raton Gulches, one-fourth mile below upper contact of Treasure Mountain formation. Powder analyzed contained about 1 per cent apatite and less feldspar.

2. Diopside from phenocrysts of Los Pinos andesite-latite (Con A) from northern part of Conejos quadrangle, Colorado, north of Green Ridge and just east of Goat Ranch. Powder analyzed contained about 1 per cent apatite and less feldspar.

3. Diopside from phenocrysts of pyroxene andesite of Sheep Mountain andesite (Sv 9), from southern part of Summitville quadrangle, Colorado. Analyzed sample contained 2 per cent each of hypersthene and groundmass. Analysis corrected for this material. Indices of refraction vary ± 0.01 from the values given, which are the average.

4. Hypersthene phenocrysts from same specimen as diopside 3 (Sv 9). Pleochroism α =pink, β =yellow, γ =green. Indices of refraction vary ± 0.01 . Powder analyzed contained about 3 per cent augite, and the analysis is corrected for this material. Indices vary ± 0.01 .

5. Diopside approaching pigeonite from San Antone basalt from Buffalo Butte, New Mexico, (NM 78). Indices vary ± 0.01 .

6. Diopside approaching pigeonite from Hinsdale basalt, railroad cut near Servilleta Plaza, N. Mex. (NM 3004). Indices vary ± 0.01 .

7. Diopside, Piedra rhyolite-latite glass (SC xx). Eastern part of San Cristobal quadrangle, Colorado, along road on north side of Rio Grande, north of mouth of Spring Creek. (SC xx glass of rock analyzed.)

8. Hypersthene Piedra rhyolite-latite, same specimen as 7 (SC xx).

9. Diopside from Hinsdale rhyolite (SC 906) from northeastern part of San Cristobal quadrangle, Colorado. Along road between Creede and Lake City at head of Big Spring Gulch.

quartz latite (1) and from the latite-andesite (2) are much alike; and they show some clinohypersthene in solid solution. The diopside from the pyroxene andesite (3), which is from the same rock as the hypersthene (4), has more clinohypersthene in solid solution than the other diopsides.

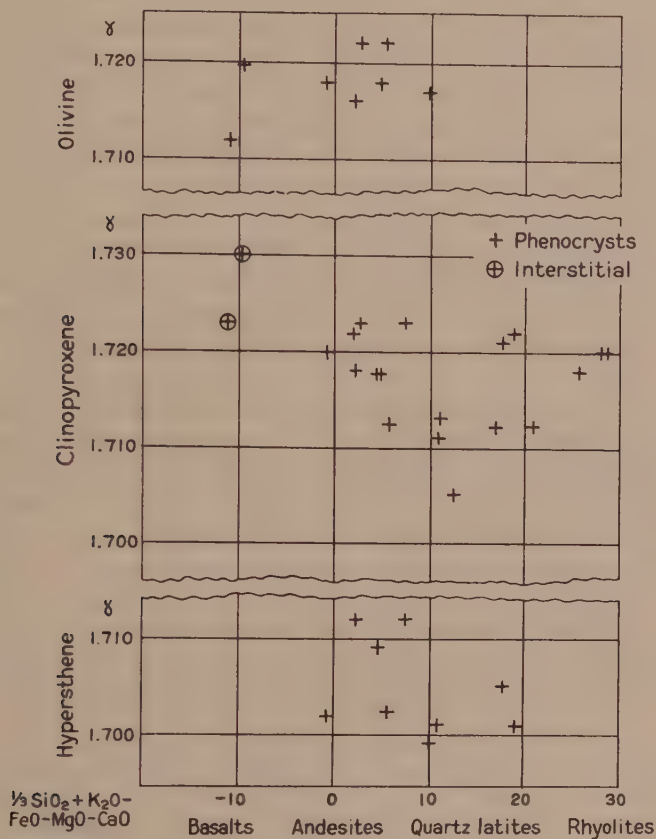


FIG. 8. The γ index of refraction of the olivines, clinopyroxenes, and hypersthene of the San Juan lavas plotted against their position between basalt and rhyolite.

The optical data indicate that the pyroxenes in the basalts have still more clinohypersthene and that they approach pigeonite in composition. MnO is higher in the pyroxenes from the quartz latites than in those from the andesites.

Optical data are given in the table for a number of pyroxenes from some of the San Juan lavas. Other unanalyzed pyroxenes were measured and the γ indices are plotted in Fig 8. The pyroxene phenocrysts show only a moderate variation in composition—from 22 to 31 per cent of

FeSiO_3 for the hypersthene, and nearly the same variation as that shown in the analyses of Table 2, for the diopsides. The pigeonites of the basalts differ more and are higher in iron and in clinohypersthene. The iron content of the pyroxenes is lower in the quartz latites than in the andesites or rhyolites, but the variation is not very regular. Without exception the values of γ for diopside phenocrysts and olivine in the same rock differ from each other by less than 0.003, and the value for the olivine tends to be lower by only 0.001. In the basalts the interstitial pyroxene has a value for γ about 0.010 greater than that of the olivine in the same rock. The γ for hypersthene shows less similarity to that of diopside and is from 0.007 to 0.021 lower, averaging about 0.014 lower; β averages about the same for the two pyroxenes.

These data indicate that the iron is distributed systematically between the olivine and the diopside and that the ratio $\text{MgO}/\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MnO}$ is higher in olivines than in the diopsides that accompany them. The hypersthene is less systematic in its iron content, but in general it has about the same $\text{Mg}/\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MnO}$ ratio as the diopside that accompanies it.

The tendency for the pyroxene phenocrysts in the pyroxene andesites to have more iron than those of the quartz latites and rhyolites is not in accordance with what we would expect from the physical chemistry of the pyroxene systems¹⁴ nor does it agree with the data of Tsuboi for Japanese rocks. Tsuboi found that the pyroxene phenocrysts have higher indices of refraction as the feldspar becomes poorer in lime.

For the White Mountain magma series, a group of mildly alkaline rocks, Chapman and Williams found "a great increase in iron relative to magnesia in going from the basic to the siliceous end of the series."¹⁵

Barth¹⁶ found that in basalts the clinopyroxene phenocrysts as com-

¹⁴ Vogt, J. H. L., The physical chemistry of the magmatic differentiation of igneous rocks, Part 1: *Vidensk. Skr.*, **1**, *Mat. Naturv. Klasse*, no. 15, pp. 100-118, Kristiania, 1924.

Fenner, C. N., The crystallization of basalt: *Am. Jour. Sci.*, 5th ser., vol. **18**, pp. 225-253, 1929.

Bowen, N. L., *The evolution of the igneous rocks*, pp. 79-81, Princeton Univ. Press, 1928.

Bowen, N. L., and Schairer, J. F., The system $\text{MgO}-\text{FeO}-\text{SiO}_2$: *Am. Jour. Sci.*, 5th ser., vol. **29**, pp. 159-160, 1935.

Tsuboi, S., On the course of crystallization of pyroxenes from rock-magmas: *Japanese Jour. Geol. and Geog.*, vol. **10**, pp. 67-82, 1932. (See Fig. 4; the text, p. 74, makes the reverse statement.)

¹⁵ Chapman, R. W., and Williams, C. R., Evolution of the White Mountain magma series: *Am. Mineral.*, vol. **20**, p. 514, 1935.

¹⁶ Barth, T. F. W., Crystallization of pyroxenes from basalts: *Am. Mineral.*, vol. **16**, pp. 195-208, 1935.

Powers, H. A., Differentiation of Hawaiian lavas: *Am. Jour. Sci.*, 5th Ser., vol. **30**, pp. 57-71, 1935.

pared with those of the groundmass are poorer in iron as well as in clinohypersthene. Kuno and Sawatari¹⁷ found the pyroxene phenocrysts of two basalts from Japan to be zoned diopside with the borders richer in iron than the cores, and Kuno has shown that this holds for both the augites and olivines from the Alaid volcano.¹⁸

This decrease in the ratio total Fe as FeO/MgO from the pyroxene of the basalts to those of the rhyolites in the San Juan rocks is in contrast to the increase in this ratio in the rocks themselves, from $1\frac{1}{2}$ in the average of the San Juan basalts to 7 in the average of the rhyolites with about 75 per cent SiO_2 . In the rhyolites the iron is mostly in the form of oxides, magnetite, hematite, and ilmenite.

The apparent inconsistency is not easily explained—that the pyroxenes which crystallized later in any single rock are richer in iron than those that crystallized earlier, although in a differentiation series the pyroxenes of the late, low-temperature members (rhyolitic rocks) have a lower Fe/Mg ratio than those of the earlier members (basaltic rocks), and even though in the rocks as a whole the Fe/Mg ratio is greater in the late rocks.

The crystallization of the pyroxenes in a given rock, as shown by zoning, gives more directly the course of crystallization of the pyroxenes, and it conforms to the data on the melting phenomenon of the pyroxenes. The decrease in iron content in the pyroxenes from basalt to rhyolite is due to the fact that the iron goes into the hornblende and biotite, which are high in iron, and into the iron ore, leaving little for the pyroxenes.

CONDITIONS OF FORMATION OF PIGEONITE

In the San Juan lavas pyroxenes approaching pigeonite are confined to the basalts; these rocks contain olivine but no hypersthene. Pigeonite rarely or never occurs as good phenocrysts but is interstitial to the feldspar. In the pyroxene andesites both augite (with 22 per cent of clinohypersthene in analysis 3) and hypersthene are present, whereas in the quartz latites and rhyolites the augites contain about 10 per cent of clinohypersthene in solid solution (analyses 1 and 2). These facts indicate that a high concentration of clinohypersthene in clinopyroxenes takes place in the high-temperature rocks and decreases as the temperature of crystallization falls. At the temperature of crystallization from a basalt magma the clinopyroxene may carry all the hypersthene molecule of

¹⁷ Kuno, H., and Sawatari, M., On the augite from Wadaki, Idu, and Yoneyama, Etigo, Japan: *Japanese Jour. Geol. and Geog.*, vol. 11, pp. 328–343, 1934.

¹⁸ Kuno, H., Petrology of Alaid Volcano, North Kurile: *Japanese Jour. Geol. and Geog.* vol. 12, pp. 161–162, 1935.

the magma in solid solution; at the temperature for pyroxene andesite the clinopyroxene can carry only 24 per cent of hypersthene in solid solution; and at the temperature of crystallization of quartz latite and rhyolite the clinopyroxene can carry only 10 per cent of hypersthene in solid solution.

The above conclusion does not entirely conform to the data of Barth¹⁹ and others, who found the phenocrysts in basalt to be a diopside with less than 10 per cent excess of clinohypersthene, and the groundmass pyroxene to be an ordinary pigeonite. So far as we are aware, pigeonite is almost entirely confined to the groundmass or interstitial pyroxene. Does pigeonite form only during rapid crystallization and as an unstable form? Barth²⁰ has offered a similar explanation. Bowen and Andersen²¹ have shown that at the temperature of crystallization of melts of the pyroxenes, diopside and clinoenstatite are miscible in all proportions, but it does not follow that they are miscible in all proportions at the temperatures of crystallization of basaltic and andesitic rocks. In fact, the common association in pyroxene andesites, gabbros, and other rocks of diopside, with some clinoenstatite in solid solution, and hypersthene would seem to show that under the conditions of crystallization of a basaltic magma clinohypersthene has a limited miscibility in diopside and that the amount that can be carried in solid solution decreases with temperature. This conclusion is strengthened by the fact that in coarsely crystalline gabbros of the same composition as the diabases and basalts, pigeonite has never been described, and diopside is commonly associated with hypersthene. This indicates that when the crystallization is slow enough to allow the stable forms to crystallize, hypersthene and augite crystallize and not pigeonite.

4. OLIVINE

BY ESPER S. LARSEN AND JOHN IRVING

Olivine forms the chief or only phenocrysts in the basalts. It decreases in amount as the silica content of the rock increases and was not found in those with more than 56 per cent SiO_2 . In the quartz basalts it is

¹⁹ Barth, T. F. W., Crystallization of pyroxene from basalts: *Am. Mineral.*, vol. **16**, pp. 195-208, 1931.

Kuno, H., and Sawatari, M., On the augite from Wadaki, Idu, and Yoneyama, Etigo, Japan: *Japanese Jour. Geol. and Geog.*, vol. **11**, pp. 328-343, 1934.

²⁰ Barth, T. F. W., Mineralogical petrography of the Pacific lavas: *Am. Jour. Sci.*, 5th ser., vol. **21**, pp. 390-391, 1931.

Kuno, H., Preliminary note on the occurrence of pigeonite as phenocrysts in some pyroxene-andesite from Hakona Volcano: *Jour. Geol. Soc. Japan*, vol. **42**, pp. 39-44, 1935.

²¹ Bowen, N. L., and Andersen, O., The binary system MgO-SiO_2 : *Am. Jour. Sci.*, 4th ser., vol. **37**, pp. 487-500, 1914.

associated with quartz phenocrysts, and it is commonly present as phenocrysts in lavas that contain either cristobalite or tridymite in the gas cavities. It is also found in lavas in which there is quartz in the groundmass, or in which there is as much as 12 per cent of quartz in the norm of the rock, or 17 per cent of quartz in the norm of the groundmass.

Without exception the olivine phenocrysts show much magmatic resorption, and almost without exception they are partly altered to iddingsite. In some rocks the olivine is completely replaced by iddingsite or iron oxide. Very rarely it is altered to serpentine. In the granular intrusive rocks the alteration to iddingsite was not found, but that to serpentine is common.

The olivines vary only moderately in their optical properties. An analysis and the optical properties of a fresh olivine from the basalt of Buffalo Buttes (belonging to the Hinsdale andesite), in New Mexico, about 16 miles south of Antonito, is given in Table 3. The optical properties of the olivine from the widespread Hinsdale basalt flows of New Mexico, just south of the San Luis Valley, indicate an olivine with about 21 mol. per cent of fayalite. The γ index of refraction of eight olivines from the San Juan lavas is plotted in Fig. 8 against the composition of the lava in which the olivine occurs. The content of forsterite ranges only between 21 and 30 per cent; in general the forsterite content is higher in the less siliceous rocks.

TABLE 3. OLIVINE FROM BASALT OF BUFFALO BUTTES.

SiO ₃	39.31	$\alpha=1.675$	Opt. —, 2V near 90°
TiO ₃	0.06	$\beta=1.694$	$r>v$ perceptible
Al ₂ O ₃	1.68	$\gamma=1.712$	
Fe ₂ O ₃	None		
FeO.....	19.84		23 mol. per cent fayalite
MnO.....	0.17		
MgO.....	37.74		
CaO.....	0.87		
	99.67		

THE LAW OF COMPLICATION

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ABSTRACT

The law of complication, advanced by Goldschmidt, rests on an empirical basis. In this paper, the law is investigated rationally. It is shown that if missing terms are neglected, any zone of any crystal must conform to the law of complication for purely geometrical reasons. A transformation to ordinary Miller indices makes it obvious that the law implies the fundamental property of *permutable axes*. Strictly permutable, non-identical axes are only encountered in certain zones of certain classes of isometric, tetragonal and hexagonal crystals, because this condition requires a properly located symmetry element through the dominant node, 1. A re-examination of Goldschmidt's evidence for the reality of the law of complication indicates that this evidence points only to the *statistical* reality of the law, and that individual zones of a given crystal species do not, in general, conform to the law except in the special symmetry cases given above.

Two factors enter into mechanism of controlling the permutability of axes in a zone: the lattice frame, which limits the slopes of crystal faces to definite values but which does not prohibit any crystal from conforming to the law of complication, and the growth environment of the crystal. In any individual instance, the latter factor supplies the mechanism for making the axes of a zone non-permutable. A statistical study of a given crystal species from all environments, however, gives a mass of data from which the specific effect of any individual environment is, at least partly, eliminated. Under these circumstances, the data may fit the crystal species into the law of complication. Junghann's addition-rule aspect of the law of complication, although it implicitly includes Goldschmidt's (essentially) reciprocal term law, is a still poorer approximation because it is, without theoretical justification, still more specific.

INTRODUCTION

Peacock¹ has recently refocussed attention upon the law of complication because of its application in the calaverite problem.² This important generalization is due to Victor Goldschmidt,³ and is based primarily upon a statistical study of the frequency of occurrence of crystal faces. Goldschmidt noticed that, referred to the Goldschmidt gnomonic projection coordinates, a zone, $0 \cdot \cdot \cdot \infty$, contained the face p and its reciprocal $1/p$ with equal frequency, the simpler values of p oc-

¹ Peacock, M. A., Calaverite and the law of complication: *Am. Mineral.*, vol. 17, pp. 317-337, 1932.

² Goldschmidt, Victor, Palache, Charles, and Peacock, Martin, Über Calaverit: *Neues Jahrb. Min.*, etc., Bl. Bd., 63-A, pp. 1-58, 1932.

³ Goldschmidt, V., Über Entwicklung der Krystallformen: *Zeit. Krist.*, vol. 28, 1897. I, pp. 1-35; II, pp. 414-451.

curing more often than the complicated ones, of course. This implies that crystal faces occur in zones according to the following plans:

SERIES		COORDINATES						
N_0	0							∞
N_1	0				1			∞
N_2	0		$\frac{1}{2}$		1		2	∞
N_3	0	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{3}{3}$	1	$\frac{2}{3}$	2	∞
N_n	0	$\frac{1}{n}$	etc.		1		etc.	∞

The main point of the law of complication is that the *dominant node*, 1, stands symmetrically between reciprocals.

Goldschmidt further showed that in zones not containing the faces 0 and ∞ , the zones could be stretched to do so, so to speak, by a transformation consisting of substituting $p - p_1/p_2 - p$ for each term, p , of the original series, $p_1 \cdots p \cdots p_2$. The zone so transformed, also conforms to the law of complication. More generally, the transformation may be used rather freely to bring segments of zones into harmony with the law.

The law of complication is of current interest because of its application by students of surface morphology to the fixing of the axial ratio. As it stands, it is completely empirical. Goldschmidt was inclined to extend the law to cover the fields of music, color, and planetary astronomy, which lent it a distinctly mystical flavor. It is the partial purpose of the present paper to give a rational analysis of the law of complication and to show that it rests on a purely geometrical basis in so far as it concerns crystals.

THE LAW OF COMPLICATION

Possible Indices. Suppose that in any crystal the basal pinacoid and the unit dome are so chosen that the maximum value of h which appears in indices is the same as the maximum value of l . As an elementary instance, suppose the maximum value of h and l does not exceed 3. Omitting the k index number by confining attention to the pinacoidal profile of a zone, the only possible indices which can appear are those formed by taking all combinations of $h = 0, 1, 2, 3$, with $l = 0, 1, 2, 3$. More generally, suppose the maximum value of h and l does not exceed n . Then, the sum total of all indices which can possibly appear on the crystal can be conveniently represented by the square array:

		l				
		0	1	2	3	n
h	0	00	01	02	03	0n
	1	10	11	12	13	1n
	2	20	21	22	23	2n
	3	30	31	32	33	3n
		⋮	⋮	⋮	⋮	⋮
	n	n0	n1	n2	n3	nn

----- (1)

Several of the above combinations are identical. The only distinct ones are the following:

		l				
		0	1	2	3	n
h	0		01			
	1	10	11	12	13	1n
	2		21		23	2n
	3		31	32		3n
			⋮			
	n		n1	n2	n3	

----- (2)

If a gnomonic projection is made of the crystal and the plane of projection chosen normal to the c axis, as established in the first paragraph of this section, the possible Goldschmidt indices, p , corresponding to those given by square array, (2) are obtained by taking each index in (2), reducing it so that the l index number becomes unity, and writing only the other number corresponding to the reduced h index number, thus:

	0				
∞	1	$\frac{1}{2}$	$\frac{1}{3}$	---	$\frac{1}{n}$
	2		$\frac{2}{3}$		$\frac{2}{n}$
	3	$\frac{3}{2}$			$\frac{3}{n}$
	⋮				
	n	$\frac{n}{2}$	$\frac{n}{3}$		

(3)

The order of occurrence of these faces in the zone is as follows:

$$p = \frac{1}{n} \frac{2}{n} \frac{3}{n} \text{ etc. } \frac{1}{3} \frac{1}{2} \frac{2}{3} 1 \frac{3}{2} 2 3 \text{ etc. } \frac{n}{2} \frac{n}{3} n \quad (4)$$

The exact positions of the fractions involving n , with respect to the definite numbers of the sequence, depends upon the value of n . The symbol *etc.* stands for terms involving numbers between 3 and n . Regardless of the value of n , or the terms between 3 and n , however, array (3), from which this series is derived, indicates that any term whatever has a reciprocal an equal distance on the other side of the NW-SE diagonal. In other words, reciprocals are symmetrically placed about the dominant node, 1. This zone sequence, then, is identical with the complication series N_n .

This section may be summarized as follows: with the proper choice of axes (proper choice of basal pinacoid and unit dome, say) the collection of all possible poles of a zone in the gnomonic projection *must* obey the law of complication for purely geometrical reasons. This statement, and the development given above, neglects the possibility of missing and extra terms, which are also well known in actual crystals. These will be discussed subsequently.

Permutable Axes. It appears that the law of complication is really a complicated expression of something more simple and fundamental. If one reverses the reasoning in the last section and assumes the law of complication as empirically demonstrated, then sequence (4) may be taken as a symbolic representation of the law. A rearrangement leads to square array (3), from which a transformation to ordinary indices immediately gives arrays (2) and (1). These arrays indicate that, if a face, (hl) , is present on a crystal, a face (lh) is also present. In other words, accepting the law of complication as a postulate, it implies that, so far as crystal surface morphology is concerned, the crystallographic axes may be permuted without affecting the indices of the faces. This conclu-

sion is not at once obvious in the form of the law as given by Goldschmidt; the reason for this is that the gnomonic projection, used by Goldschmidt for the expression of the law, is a distortion on which all indices are reduced to make l equal unity. It is this distortion which renders the law apparently complex. Indeed, the law of complication might better be renamed, the *law of permutable axes*.

SIGNIFICANCE OF THE LAW

An insight into the possible significance of "permutable axes" may be gained by considering a cubic latticework: say, the two-dimensional analogue of a simple cubic lattice. In a cubic lattice, the a_1 and a_3 axes are symmetrically equivalent and therefore rigorously permutable in any sense (neglecting the modifications introduced by point-group symmetry, and considering only lattice symmetry proper). Hence, any face (hl) must necessarily be accompanied by a face (lh), provided the crystal is grown in an environment field at least as symmetrical as that of the lattice. The two faces, (hl) and (lh), are, of course, symmetrically located on either side of the unit "dome," (11), which is Goldschmidt's dominant node in the law of complication.

If the cubic lattice is slightly distorted both with regard to angle and lengths, it becomes a general two-dimensional lattice. Suppose, now, that one assumes that with each lattice point is associated a sort of discrete, self-contained, packet of atoms, both in the cubic and general cases. Then, whether the packets pile together in cubic or general array in any particular case will have very little control on which faces are left exposed on the surface, for the significance of crystal system in this case is mainly the type of packing required by the shapes of the packets themselves. In other words, with these simple assumptions, one might expect that non-cubic crystals would show a sort of quasi-equivalence of (hl) and (lh) faces corresponding to those rigorously equivalent in the cubic case.

If one modifies the simple assumptions just mentioned, and endows the lattice-point packets with directional bonds, then practical equivalence of (hl) and (lh) no longer need hold for non-isometric crystals. This is, indeed, borne out in the distribution of faces in actual crystals. The very table used by Goldschmidt to demonstrate the statistical reality of the law of complication, speaks plainly on this point. Three isometric examples are cited, two with an analysis of the zone $p0$. Both of these show ideal examples of the law of permutable axes, as they necessarily must, for a_1 and a_3 are rigorously permutable for the two examples, garnet and halite. The third example contains an analysis of the zone $p1$ in fluorite. The zone $p1$ implies reference axes, [011] and [100], which are

not equivalent. The dominant node, 1, is flanked on one side by 2 and 3 and on the other with its reciprocals, but this is the limit of the application of the law of complication, for there are, in addition, three terms on one side of the dominant not having equivalents on the other, and *vice versa*; this is to be expected in view of the non-equivalence of the reference axes [011] and [100].

The effect of non-equivalence can be extended to the analysis of zones of non-isometric crystals, for which Goldschmidt gives a list of 18 examples. Of these 18, used to prove the law of complication statistically, only two are in rigorous accordance with the law individually: diopside and copper vitriol. Every other example shows one or more terms without corresponding reciprocals. Strictly speaking, then, the law of complication is only a statistical truth. The reason for this is that, in a collection of examples used for statistical study, a certain number of faces, of a given particular type (hl) will be present. Whether this index is written (hl) or (lh), giving Goldschmidt indices, h/l or l/h respectively, will depend on the convention of choosing the first or second axis as the c axis. This is purely arbitrary in the general case, the triclinic system, and the convention bears no relation to essentials in any other system. In any statistical collection of crystals, therefore, there tends to be an equal number of faces of Goldschmidt index p and $1/p$. This is exactly what Goldschmidt found, and it is on this basis that he suggested the law of complication. It should be clearly understood that *this is of no rigorous application to any individual non-isometric crystal, or to an individual zone referable to non-equivalent axes in even an isometric crystal, or, in general, to the case of an individual zone in which the symmetry of the crystal does not require a symmetrical distribution of faces about the node 1*. In general, non-identical axes, can be rigorously permutable only in certain classes of the isometric, tetragonal, and hexagonal system.

As a particular example of this feature, the 0 q zone of a pyrite crystal of cubo-pyritohedral habit may be cited. The zone sequence is:

$$\begin{array}{ccccccc} \text{indices:} & 001 & \cdot & \cdot & 021 & 010 & \\ q = & 0 & \cdot & \cdot & 2 & \infty & (5) \end{array}$$

Not only is there no arrangement of reciprocals about the dominant node, 1, in this case, but the dominant itself is absent. Furthermore, the law of complication is not necessarily followed by the crystal even when this simple cubo-pyritohedral habit becomes more ornate by development of additional faces. The truth of this can be instantly grasped by a glance at the figures of pyrite collected by Goldschmidt.⁴ The reason why

⁴ Goldschmidt, Victor, *Atlas der Kristallformen*, 6, 1920, Tafel 116, figures in the region of 247–250, for example.

pyrite does not adhere to the law of complication is that its point-group does not contribute a properly located symmetry element through the dominant node, 1, and therefore there is no strict requirement for equivalent faces on each side of this node.

This non-equivalence of axes gives rise to missing or extra terms in the complication series. Thus, in series (5) above, the term $\frac{1}{2}$ is missing, or the term 2 may be regarded as extra, depending on the viewpoint. In many actual examples, the number of missing or extra terms is not large and the correspondence of important simple terms with those required by the ideal law of complication is good. Thus in Goldschmidt's statistical table used to demonstrate the law of complication, the term 1 appears in each of the 21 examples, as do also the terms 0 and ∞ ; the term 2 and $\frac{1}{2}$ find their reciprocals missing nine times, the terms $\frac{3}{2}$ and $\frac{2}{3}$ find their reciprocals missing twelve times; but the more complicated terms do not give the law of complication much backing.

MODIFYING CONDITIONS

Cause of Non-permutable axes. It is evident that, for a particular crystal having axes rigorously non-permutable in the zone in question, the law of complication is, at best, an approximation. It is now desirable to inquire into the nature of certain factors rendering the axes non-permutable in an effort to ascertain to what extent the law of complication may be used.

• The entire law of complication as usually recognized, rests on the appropriate appearance of external crystal faces. The appearance of a crystal face is conditioned by two factors:

(a) A crystal face can only appear parallel to a lattice plane. The lattice is the framework of crystal faces, and it provides the most fundamental control on their appearance by restricting slopes to certain permitted values. If it were the only factor in the appearance of faces, i.e., if every lattice plane appeared as a face on the crystal, then every crystal would rigorously conform to the law of complications in its major aspect of providing reciprocal terms symmetrically arranged about the dominant node, 1. Furthermore, it would conform to the law regardless of the choice of direction of crystallographic axes. This follows from the fact that permuting any two crystallographic axes only has the effect of permuting the index numbers corresponding to them. The more formal proof follows the lines indicated in the section entitled *Possible Indices*.

If, instead of studying a crystal by means of the reflection of visible light from external planes, it is studied by means of light of x -ray wavelength reflected from internal planes, then the additional variables regulating the appearance of external faces are of no importance, and the

collection of planes so determined conforms rigorously to the law of complication in its reciprocating aspect. This statement must be qualified by noting that the complication series so determined contains missing terms due to systematic extinctions caused by space group and atom parameter requirements.

(b) The second factor which limits the appearance of external faces is the accident of environment in which the crystal made its appearance and continued growth. This set of variables is very complex, but the general nature of its control is known. Generally speaking, the faces which appear on the surface of a crystal are those whose growths are too slow to permit them to be eliminated at the expense of other faces during the growth process. This may mean either that the face in question would not have been eliminated, or it may mean that it was on its way toward elimination, but that the process was arrested by interruption of the growth of the crystal. The last point is important, for it implies that the forms observed on crystals are not necessarily equilibrium ones; the elimination of a face of this sort depends on the size of the crystal under observation, small crystals having a richer variety of faces which are less representative of conditions of growth.

The relative growth velocities of crystal faces depend on a number of conceivable factors, among which position in coordination energy series,⁵ temperature, supersaturation and especially impurity content of solution are important.⁶ The last general factor has been the theme of the researches of Buckley,⁷ who has been able to show that an impurity is able to impede the growth of a crystal face provided the impurity ion (etc.) has a configuration and nature comparable with units exposed on the crystal face. This means that in all but the simplest and purest possible artificial solutions, the habit of the crystal is controlled by variables of a very complex nature.

⁵ The following papers give an introduction to this subject:

Stranski, I. N., Wachstum und Auflösen der Kristalle vom NaCl-Typ: *Zeit. physik. Chemie*, vol. **17B**, pp. 127–154, 1932.

Anderson, Paul A., The molecular process of crystal growth in hexagonal metals. Deposition upon monocrystalline hemispheres of zinc: *Physical Review*, vol. **40**, pp. 596–606, 1932.

⁶ Many authors emphasize “recticular density” as a factor. The very term itself, however, has lost its significance since it has become apparent that crystals generally are not built of molecular units, and that the units are not generally bonded by central forces. In place of “recticular density,” a coordination energy series is important.

⁷ Buckley, H. E., The crystallization of potash-alum and the effect of certain added impurities on its habit: *Zeit. Krist.*, vol. **73**, pp. 443–464, 1930. This is the first of a series of papers by this author. Further contributions have appeared in the same place from time to time up to the present year.

APPROXIMATION FOR A SINGLE SPECIES

As mentioned previously, the first requirement, (a), puts very little restriction on the development of crystal faces. The second, (b), however, is the one which supplies the mechanism for actually making the axes of a zone non-permutable, for the structural configurations of faces related by the permuted indices are not the same. For any given impurity in the solution, a particular crystal will, therefore, develop a certain set of faces, which will not, in general, be in accord with the law of complication. There are two alleviating circumstances, however: Small crystals may not have grown sufficiently to eliminate fast-growing faces, and a small crystal, may, therefore, be more nearly in accord with the law of complication. Secondly, if the study of a crystal species is based, not on a single individual, or on a single crop, or on the representatives of a single mineral locality, but rather if the study is based on numerous crystals grown under a wide range of varying conditions, or on minerals from a large number of localities, then the study takes on a statistical aspect. In this case, there is a chance that differing solutions and other conditions bring out different sets of faces, and that, therefore, the sum total of all the faces represents a large number of the possible simple lattice planes. This tends to eliminate the low symmetry effect of an individual growth environment.

It is possible therefore, to utilize the law of complication if one does not expect perfect agreement with it, provided the comparison with the ideal law is made with the accumulation of all known crystal faces of the species in question, and provided that a rather large number of observations has been made on crystals from many environments. As a matter of fact, it is a statistical mass of data of this sort to which Goldschmidt has applied his law of complication.

It should be pointed out that this means of fixing the lattice of a crystal actually consumes months of time for the accumulation of the necessary data, not to mention the fact that one is never sure whether the mass of data is really sufficient for the purpose. Against this one should weigh the *unique* method of fixing the lattice within a few days' time which is possible by *x*-ray means, utilizing the Weissenberg⁸ method.

It should also be pointed out that *x*-ray methods are unique simply because they do not depend on the development of *surface* planes but rather upon internal planes. *X*-ray methods fix the lattice uniquely because they study the lattice directly; ordinary optical reflection methods

⁸ Turnell, George, Determination of the space-lattice of a triclinic mineral by means of the Weissenberg *x*-ray goniometer: *Am. Mineral.*, vol. 18, pp. 181-186, 1933.

are non-unique because they study this fundamental structure as modified by other complex variables,—because they thus study a secondary property.

Special Cases. There is one group of special cases in which individual actual crystals with non-permutable axes may nearly conform to the law of complication, namely: the appropriate zone of a crystal which is based upon a high symmetry isometric frame, or more generally, the appropriate zone of a crystal whose axes are semi-permutable because they correspond to really permutable axes in a framework of proper symmetry. The simplest example of this is a crystal whose essential structural plan is simple, but which has a superstructure which lowers the symmetry. The compound AuCu is a representative of this relation. Both Au and Cu alone have cubic close-packed structures; the compound AuCu also has a cubic close-packed structure if one does not distinguish between Au and Cu atoms. The mutual arrangement of these two sorts of atoms, however, gives the space pattern of the compound tetragonal symmetry. PtCu, similarly, has a rhombohedral superstructure modification of cubic close-packing. β -brass, CuZn, must also belong to this class of crystals. Its essential arrangement is body-centered cubic (usually spoken of by metallographers, however, as cesium chloride type); it is thought to have a cubic superstructure, but actually the crystals are anisotropic by reflected, polarized light, so the symmetry is no greater than tetragonal. A slightly different aspect of this relation is given by martensite, which is α -iron with up to 6% carbon. This has an essentially body-centered cubic structure with a few carbon atoms placed interstitially in such a way as to degrade the symmetry of the structure to tetragonal. Unfortunately, crystals of these compounds are not known with well-enough developed faces to test their approximate conformation to the law of complication.

THE ADDITION RULE

Finally, it should be noted that the appearance of crystal faces in the law of complication is an aspect of the addition rule.⁹ This is easy to see in a simple series, say N_3 . Combinations of all possible index numbers up to 3 give:

$$\text{indices} = 01 \quad 13 \quad 12 \quad 23 \quad 11 \quad 32 \quad 21 \quad 31 \quad 10 \quad (6)$$

$$N_3 = \underline{0} \quad \frac{1}{3} \quad \frac{1}{2} \quad \frac{2}{3} \quad 1 \quad \frac{3}{2} \quad 2 \quad 3 \quad \infty \quad (7)$$

It will be observed that the addition of any two indices separated by an

⁹ Rogers, Austin F., The addition and subtraction rule in geometrical crystallography: *Am. Mineral.*, vol. 11, pp. 303–315, 1926.

odd number of indices, gives the index half way between the two. This property can be easily demonstrated in simpler cases down to the limiting series, N_1 . This suggests that it can also be generalized to higher series. If so, the next higher series, N_4 , can be produced by adding adjacent indices to obtain the new ones appearing between them. Applying this to (6) gives,

$$01 \ 14 \ 13 \ 25 \ 12 \ 35 \ 23 \ 34 \ 11 \ 43 \ 32 \ 53 \ 21 \ 52 \ 31 \ 41 \ 10 \quad (8)$$

$$0 \ \frac{1}{4} \ \frac{1}{3} \ \frac{2}{5} \ \frac{1}{2} \ \frac{3}{5} \ \frac{2}{3} \ \frac{3}{4} \ 1 \ \frac{4}{3} \ \frac{3}{2} \ \frac{5}{3} \ 2 \ \frac{5}{2} \ 3 \ 4 \ \infty \quad (9)$$

The corresponding series of Goldschmidt indices (9) has the new terms $\frac{1}{4}$, $\frac{2}{5}$, $\frac{3}{5}$, $\frac{3}{4}$, and their reciprocals. These new terms are just the ones which Goldschmidt's statistical study indicates to actually occur next in order of importance, and series (9) is indeed complication series N_4 . Further tests of the addition rule in predicting actual complication series cannot be completely carried out, for lack of sufficient data on the more complicated faces. It can be said, however, that the terms which Goldschmidt's statistical study indicates to occur next most abundantly are among those to be obtained by an extension of the addition rule. Goldschmidt arrived at an identical ideal complication series by what he believed to be the rules of combination of crystal forces to give crystal faces.¹⁰

The occurrence of faces according to the addition law was first recognized in anorthite by Junghann.¹¹ Subsequent writers have investigated this property empirically for other crystals, as well as theoretically. A summary of the development of this subject is given by its latest contributor, Baumhauer.¹²

Goldschmidt's statement of the law of complication may be said to be included in Junghann's empirical addition law. Thus, given any two pinacoids, the indices are taken as 01 and 10. Adding these gives 11, which gives the first Goldschmidt series N_1 , etc. Junghann's law is more restrictive than Goldschmidt's, however, for it definitely predicts the required new indices for any given complication. Actually, Goldschmidt's law does the same, but in his case, more emphasis has been laid on the symmetrical arrangement of reciprocal terms on each side of the dominant, which gives it a more general aspect. It should be pointed out

¹⁰ Reference 3.

¹¹ Junghann, Gustav, Ein einfaches Gesetz für die Entwicklung und die Gruppierung der Krystallzonen: *Pogg. Ann.*, vol. 152, pp. 63-95, 1874.

¹² Baumhauer, H., Untersuchungen über die Entwicklung der Krystallflächen im Zonenverbände: *Zeit. Krist.*, vol. 38, pp. 628-655, 1904.

that up to the series N_3 , there is no difference between Junghann's rule and Goldschmidt's (essentially reciprocal) law, because N_3 uses every possible combination of $h=0, 1, 2, 3$ with $l=0, 1, 2, 3$. In the next sequence, N_4 , all combinations with 4, and some, but not all, combinations with 5, enter (see sequences (6), (7), (8), and (9)). Higher series are still less regular, according to the strict interpretation of the addition rule. In spite of Goldschmidt's statistical evidence, however, it is the reciprocating aspect which individual crystals most nearly obey, not necessarily the addition principle. Thus, anorthite, which Junghann¹¹ used to demonstrate the addition rule, conforms to that rule without missing terms only to N_1 , beyond which it is abnormal. Goldschmidt's law implies permutable axes in all crystals, while the addition rule, strictly applied not only implies this but much more with regard to the appearance of particular faces. Needless to say, crystals are found to conform more nearly to the less restrictive Goldschmidt reciprocal term approximation than to the highly restrictive addition rule approximation.

SUMMARY

1. A rational derivation of the reciprocal term aspect of the law of complication is given, and it is shown that the significance of the law is more easily understood divorced from the gnomonic projection. It is then evident that the law of complication might better be renamed the *law of permutable axes*.

2. The law of complication is, at best, a poor approximation, both theoretically and as shown by actual crystals. It implies permutable axes in the zone in question, which are actually only realized in certain zones of certain classes of the isometric, tetragonal and hexagonal systems. A rigorous application of the law of complications can only be made for a crystal having an appropriately located symmetry element through the dominant node, 1.

3. The lattice proper does not restrict the application of the law of complication, but the growth of external faces supplies the mechanism for the non-permutable character of axes. However, if the crystal species is studied statistically, i.e., if the comparison with the law is made on the basis of crystals from many growth environments, then the effect of any particular environment may be, in part, eliminated. Only in this way can the law of complication be compared with the actual occurrence of crystal faces.

4. Certain crystals based on cubic, tetragonal or hexagonal patterns, but with a superstructure, may conform to the law of complication.

5. The strict addition rule is a still worse approximation to the actual occurrence of crystal faces than Goldschmidt's law of complication in its reciprocal term aspect, because the addition rule is still more restrictive, with no better theoretical basis.

TWO DIOPSIDES FROM SOUTHERN CALIFORNIA*

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ABSTRACT

Exceptionally pure diopsides occur in the limestone contact zones at Crestmore near Riverside, and at Cascade Canyon near Upland, California. Chemical analyses and optical properties of both samples, especially that from Cascade Canyon, are close to published values for artificial diopside.

INTRODUCTION

The Crestmore quarries are located about two miles northwest of Riverside, California, on the west bank of the Santa Ana River, near the San Bernardino County line (Fig. 1). The locality has long been known for the large number of minerals which occur in a restricted area. The geology of the quarries has been described recently by Daly.¹



FIG. 1

The diopside was found on the south side of the Wet Weather quarry, in the limestone side of the contact zone which seems to have developed about quartz monzonite porphyry dikes. The diopside is pale green (lumiere green², 29' GGY-b), and commonly occurs in masses of interfering

* Presented before the Geological Society of America, Cordilleran Section, April 17, 1936.

¹ Daly, John W., *Am. Mineral.*, vol. 20, pp. 638-659, 1933.

² Ridgway, Robert, *Color Standards and Color Nomenclature*, 43 pp. and 53 pls., Washington, 1912.

crystals ranging up to two centimeters in length, and associated with vesuvianite, crestmoreite and interstitial calcite. Isolated well formed crystals of pale diopside are also found in a matrix of sky-blue calcite. These crystals are sometimes elongated parallel to the a -axis.

Cascade Canyon, the source of our second sample, is located on the northwest slope of Ontario Peak (Fig. 1). This locality also is remarkable for the large number of minerals to be found in a zone of varied metamorphic rocks, which extends up and down the canyon for a mile or more. Noteworthy minerals, in addition to the diopside, are lapis lazuli (perhaps sodalite or haüyne), corundum in barrel shaped crystals, glaucophane(?), fuchsite, and a black iron sulphide having many of the properties of hydrotroilite.

The diopside is found near the mouth of Cascade Canyon where it is crossed by the U. S. Forest Service fire control road, in the SE. $\frac{1}{4}$ of sec. 36, T. 2 N., R. 8 W., San Bernardino base and meridian. The material is snow white and fine grained. A fibrous, pale blue mineral which optical and chemical examination has shown to be soda tremolite occurs on the cleavage planes of the rock. Some samples also show much intermixed white tremolite, visible with a lens. Other samples consist of diopside nearly free from contamination.

OPTICAL PROPERTIES

Optical and crystallographic constants of both occurrences correspond closely to those of the artificial mineral. The indices of refraction were determined by the immersion method in monochromatic light, using a sodium vapor lamp and variable temperature apparatus, with an accuracy of $\pm .001$ or better. The values for the Crestmore material are slightly higher than those for either the artificial or the Cascade Canyon material. This is probably due to the higher percentage of iron in that from Crestmore. Table 1 gives the optical and crystallographic constants.

TABLE 1. OPTICAL AND CRYSTALLOGRAPHIC CONSTANTS OF DIOPSIDES

	<i>Artificial*</i>	<i>Crestmore</i>	<i>Cascade Canyon</i>
N_γ	1.694	1.695	1.693
N_β	1.6715	1.675	1.671
N_α	1.664	1.666	1.663
$N_\gamma - N_\alpha$	0.030	0.029	0.030
$Z \wedge c$	$38^\circ 30'$	$39^\circ 10'$	.....
$2V$	59.3°	59°	
$a \wedge c$	$74^\circ 9'$	$74^\circ 45'$	.....

* Wright, F. E., and Larsen, E. S., *Am. Jour. Sci.*, vol. 27, p. 1, 1909.

$2V$, extinction on $010(Z \wedge c)$ and the angle $a \wedge c$ were determined for the Crestmore mineral. However, the Cascade Canyon material lacks

crystal form and is too finely granular to make possible any measurements other than indices of refraction. The results, as shown in the table, agree fairly well with those for the artificial substance.

Unusual cleavage is shown by both samples. The usual diopside cleavage is prismatic, with (100) and (001) less common. The Crestmore mineral has good (100) and (001) cleavages, but prismatic cleavage develops only on thin sections which have been roughly ground. The Cascade Canyon diopside has very good basal cleavage or parting but none other of importance. Its flaky and almost micaceous character is suggestive of the variety of diopside sometimes called malacolite.

X-RAY EXAMINATION

X-ray powder photographs by W. H. Dore of the University of California, at Berkeley, indicate that both minerals are of identical structure. Spacings calculated from these patterns check closely with values calculated from data given by Wyckoff,³ thus positively identifying both our samples as diopside.

CHEMICAL COMPOSITION

Preliminary to the final quantitative analysis, both minerals were examined spectrographically by Dr. T. G. Kennard of the Claremont Colleges. The results are shown in Table 2.

TABLE 2. SPECTROGRAPHIC ANALYSIS OF DIOPSIDES

<i>Element</i>	<i>Crestmore</i>	<i>Cascade Canyon</i>
calcium	large	large
magnesium	large	large
silicon	large	large
iron	medium to small	small
aluminum	small	small
sodium	....	very small
manganese	trace	trace
silver	minute trace	....
copper	minute trace	minute trace
lead	minute trace	....
titanium	minute trace	trace
lithium	....	trace
strontium	....	trace
vanadium	....	minute trace
lanthanum	trace?	....

The analyses of both minerals show that they are essentially of the composition $\text{CaMg}(\text{SiO}_3)_2$. The first column of Table 3 gives the analysis of an artificial diopside prepared by F. E. Wright and E. S. Larsen.⁴

³ Wyckoff, Ralph, W. G., *The Structure of Crystals*, p. 418, 1924.

⁴ *Loc. cit.*

It is this mineral which Winchell⁵ uses as the end member for the diopside-hedenbergite series. The figures for the Cascade Canyon diopside are the actual analysis but the Crestmore values have been recalculated omitting 1.47% calcite matrix, which was an impurity in the sample taken for analysis. The Cascade Canyon mineral is essentially the purer of the two minerals and has but very small amounts of iron and aluminum.

TABLE 3. CHEMICAL ANALYSES OF DIOPSIDES

	A	B	C	CaMg(SiO ₃) ₂ (theoretical)
SiO ₂	55.59%	56.50%	54.54%	55.48%
CaO	25.73	25.56	24.76	25.90
MgO	18.61	17.80	17.23	18.62
FeO	.....	.....	0.30	.....
Fe ₂ O ₃	0.18	0.24	0.93	.....
Al ₂ O ₃	.....	0.12	1.28	.....
H ₂ O+	.....	0.58	0.64	.....
H ₂ O-	.....	0.22	0.32	.....
Cl	trace	.....	.....	.....
Total	100.11	101.02	100.00	100.00

A—Artificial diopside prepared by F. E. Wright and E. S. Larsen.

B—White diopside, Cascade Canyon, Calif. J. D. Laudermilk, analyst.

C—Diopside, Crestmore, Calif. Richard Merriam, analyst.

The other relatively pure diopsides which have been described also occur in limestone contact zones. A notable example is that used by Warren and Bragg⁶ in *x*-ray analysis. This diopside, from De Kalb, New York, has optical properties⁷ and composition rather close to those of our Crestmore mineral. Another case is that described recently by M. A. Peacock⁸ from xenoliths in a New Mexican quartz monzonite. In this case FeO is 0.97%, Al₂O₃ 2.55%. Indices run about .010 above those of our Cascade Canyon sample. So far as we know the Cascade Canyon material is the purest natural diopside for which both chemical and optical properties have been determined.

⁵ Winchell, A. N., Studies in the pyroxene group: *Am. Jour. Sci.*, 5th series, vol. **6**, p. 504, 1923.

⁶ Warren, B., and Bragg, W. L. *Zeit. Krist.*, vol. **69**, pp. 168–193, 1929.

⁷ Zimanyi, K., *Zeit. Krist.*, vol. **22**, p. 343, 1893.

⁸ Peacock, M. A., *Am. Mineral.*, vol. **21**, pp. 318–320, 1936.

CRYSTALLOGRAPHY OF LIVINGSTONITE

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ABSTRACT

Crystallographic measurements on livingstonite from Huitzuco, Guerrero, Mexico—the first to be made on this species—give the following data: Monoclinic; prismatic— $2/m$; $a:b:c=3.7572:1:5.3660$; $\beta=104^\circ 10'$. Elongated $[010]$. Forms: $c\{001\}$ perfect cleavage, $a\{100\}$, $d\{101\}$, $e\{\bar{1}01\}$, $p\{\bar{1}11\}$, $q\{122\}$; uncertain: $\{\bar{1}\bar{1}.1.0\}$, $\{011\}$, $\{111\}$, $\{122\}$. Space group, $C_{2h}^5-P2_1/c$; $a_0=15.14$, $b_0=3.98$, $c_0=21.60$; $\beta=104^\circ$. Cell content (provisional), $Hg_4Sb_{16}S_{28}$.

Livingstonite, a sulphide of antimony and mercury, was named in 1874.¹ The lead-gray color and prismatic habit suggested similarity with stibnite, but as yet no crystallographic measurements have been published.

A matrix specimen with embedded crystals of livingstonite from the type locality, Huitzuco, Guerrero, Mexico, was kindly provided for study by Dr. W. F. Foshag of the United States National Museum. The crystals are minute needles, 0.25 to 0.5 mm. long and less than 0.1 mm. thick, soft and flexible and difficult to handle. Eight of these were measured by Dr. H. Berman on the two-circle goniometer. They proved to be monoclinic, acicular, elongated with $[010]$, which is the convenient zone of reference. This zone exhibits the forms $c\{001\}$, $a\{100\}$, $d\{101\}$, $e\{\bar{1}01\}$. The forms determined with certainty, each by several good measurements, are: $c\{001\}$, $a\{100\}$, $d\{101\}$, $e\{\bar{1}01\}$, $p\{\bar{1}11\}$, $q\{122\}$; in addition, single observations were found to correspond to the symbols: $\{\bar{1}\bar{1}.1.0\}$, $\{011\}$, $\{111\}$, $\{122\}$. Until confirmed, these are best regarded as uncertain forms. Like development of equally frequent right- and left-hand ends indicates holohedral symmetry.

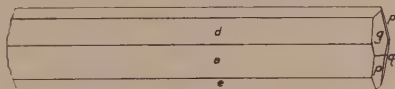


FIG. 1. A typical crystal of living stonite.

Table 1 gives the geometrical elements of livingstonite, derived from the best measurements, and the mean measured and calculated two-circle angles for the accepted forms. The polar elements and angles refer to the projection on the plane normal to $[010]$, the axis of prismatic development of the crystals.

¹ Barcena, M., *El Minero Mexicano*; notice in *Am. Jour. Sci.*, vol. 8, p. 145, 1874.

TABLE 1

Livingstonite— HgSb_4S_7 . Monoclinic; prismatic— $2/m$ $a:b:c=3.7572:1:5.3660$; $\beta=104^\circ 10'$ $r_2:p_2:q_2=0.1922:0.2745:1$; $\mu=75^\circ 50'$				
Forms	Measured		Calculated	
	ϕ_2	ρ_2	ϕ_2	ρ_2
c 001	$75^\circ 50'$	$90^\circ 00'$	$75^\circ 50'$	$90^\circ 00'$
a 100	0 39	90 00	0 00	90 00
d 101	29 53	90 00	$30\ 05\frac{1}{2}$	90 00
e $\bar{1}01$	140 29	90 00	$140\ 40\frac{1}{2}$	90 00
p $\bar{1}11$	140 29	16 23	$140\ 40\frac{1}{2}$	16 23
q 122	47 00	14 34	45 19	14 41

STRUCTURE CELL AND SPACE GROUP

These were determined with Dr. Berman's assistance by a rotation photograph about [010] and Weissenberg photographs of the zero and first layer lines about the same axis, using copper radiation.

$$a_0 = 15.14 \pm 0.04, b_0 = 3.98 \pm 0.01, c_0 = 21.60 \pm 0.04; \beta = 104^\circ$$

$$a_0:b_0:c_0 = 3.80:1:5.43; V = 1262 \times 10^{-24}$$

The ratio of the cell sides is in fair agreement with the morphological ratio, $a:b:c=3.758:1:5.366$, which is remarkable for the relative shortness of the b -axis.

The molecular weight of the cell content (M) is given by $M=dV/A$, where d is the density $(4.81)^2$, V is the volume of the unit cell (1262×10^{-24}) , A is the reciprocal of Avogadro's number. Whence $M=3679$.

Using Venable's analysis of livingstonite,² the atomic content of the unit cell is given as follows:

	Wt. per cent	Mol. ratio	$M \times \text{Mol. ratio}/100$
S.....	23.75	0.738	27.15
Sb.....	53.75	0.442	16.26
Hg.....	22.52	0.112	4.12

Accepting the numbers in the last column as 28, 16, 4, respectively, the cell formula is $\text{Hg}_4\text{Sb}_{16}\text{S}_{28}$ or $4(\text{HgSb}_4\text{S}_7)$. Since both the analysis and density represent early determinations the above cell formula cannot be regarded as entirely certain.

The space group of livingstonite is $C_{2h}^5 - P2_1/c$, which is determined by the holohedral symmetry and the following facts:

$h0l$ halved when h is odd
 $h0l$ halved when l is odd
 $h0l$ halved when $h+l$ is odd
 010 halved.

² Dana, *System of Mineralogy*, v. 109, 1892.

SPECTROGRAPHIC EXAMINATION OF SIAMESE ZIRCONS

T. G. KENNARD* AND DAVID H. HOWELL

Although many chemical analyses of zircons have been made, few spectrographic investigations have been reported. Pereira-Forjaz¹ has examined spectrographically a Portuguese zircon, and Wild² has investigated the arc spectrum of red, brown and blue Siamese zircons. The cause of the color in zircons generally has been attributed to the presence of impurities, particularly iron, copper, titanium, chromium, vanadium, zinc, uranium, thorium, hafnium and magnesium^{3,4,5}

PREPARATION OF SAMPLES

The Siamese zircons examined were said to have originated in the province of Annam, French Indo-China.⁶ All specimens were water-worn and exhibited no crystal faces. Color comparisons were made by placing a number of fragments, approximately 1 mm. thick, with random orientation, on a piece of white paper and comparing with Ridgway's Standards.⁷

The brown zircons were mine-rough specimens, while the blue were said to have been recolored from brown mine-rough by the action of heat alone, and the water-white or colorless from brown mine-rough by the use of both chemicals and heat.⁸

Samples for spectrographic examination were prepared as follows: the zircons were crushed in an agate mortar and then examined under a

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¹ Pereira-Forjaz, A., *Compt. rend.*, vol. **164**, p. 102, 1917.

² Wild, Georg O., *Centralbl. Min.*, vol. **1933A**, pp. 75-77.

³ Stevanovic, S., *Zeit. Krist.*, vol. **37**, pp. 247-256, 1903.

Eppler, W. F., *N. Jahrb. Min., Abt. A., Beil.-Bd.* **55**, pp. 401-487, 1926-27.

⁴ Spezia, G., *Zeit. Krist.*, vol. **33**, pp. 636-637, 1900.

Herman, *Zeit. anorg. Chem.*, vol. **60**, p. 369, 1908.

Brauns, R., *Centralbl. Min.*, vol. **1928A**, p. 343.

Strutt, R. J., *Proc. Roy. Soc.*, vol. **89A**, pp. 405-407, 1914.

Sandberger, *N. Jahrb. Min.*, vol. **1845**, pp. 143-144.

Klemm, R., *Centralbl. Min.*, vol. **1927A**, pp. 267-78.

⁵ Doelter, C., *Das Radium und die Farben*, Dresden, 1910.

Alexander, Jerome, *Colloid Chemistry. Theoretical and Applied*, vol. **III**, pp. 270-273, 1931.

⁶ The material was supplied by Mr. C. A. Allen, Cranbury, N.J. Grateful acknowledgment of his kind and valuable co-operation is hereby made.

⁷ Ridgway, *Color Standards and Color Nomenclature*, Washington, 1912.

⁸ Private communication from C. A. Allen. The heat treating is described in *Gems and Gemology, Heat Treating Zircons*, Allen, C. A., vol. **1**, pp. 341-344, 1935. The chemicals often employed are as follows: one ounce of arsenous acid, one ounce of silver nitrate and five ounces of soda hypophosphite, thoroughly mixed.

microscope. Only material free from inclusions and color spots, visible under a magnification of $35\times$, was selected. This material is designated as "clear" or "inclusion-free." Sample No. 10 was found to be coated with a grayish white glaze, presumably due to the chemicals used in heat-treating. This glaze was removed and spectrographically examined as sample No. 10a; the included black spots and zones of black material composed sample No. 10b. The inclusions removed from samples Nos. 1, 2, and 3 (brown mine-rough) were red in color, and in No. 2 black spots

TABLE 1.

Sample Number	Color	Ridgway's Standard (7)	Density
1.	Brown	13' <i>j.</i>	4.738
1a.	Red (inclusions)	4 <i>j.</i>	—
2.	Brown	13''' <i>a.</i>	4.744
2a.	Red (inclusions)	4 <i>j.</i>	—
	Black (inclusions)	—	—
3.	Brown	17''' <i>f.</i>	4.628
3a.	Red (inclusions)	4 <i>j.</i>	—
4.	Blue	43'' <i>d.</i>	4.719
5.	Blue	44' <i>d.</i>	4.710
6.	Blue	44 <i>e.</i>	4.734
7.	Blue	44' <i>e.</i>	4.702
8.	Straw-yellow	14 <i>g.</i>	4.613
9.	Water-white	—	4.712
10.	Water-white	—	4.622
10b.	Black (inclusions)	—	—
11.	Water-white	—	4.644
11a.	Red (inclusions)	4 <i>j.</i>	—
12.	Water-white	—	4.622
12a.	Red (inclusions)	4 <i>j.</i>	—
13.	Water-white	—	4.710
13a.	Red (inclusions)	4 <i>j.</i>	—

were also found. The red spots corresponded with those of the clear water-white samples, with a color approximating 4 *j.*⁷

In all the zircons, distinct spots or zones, or both, appeared as inclusions when examined under a magnification of $35\times$. Separation of clear portions for samples, in the crushed material, was comparatively simple except in the case of the blue variety. Here the inclusions consisted of a relatively small number of black spots distributed throughout the entire sample. No separation was made, since the material as a whole was practically inclusion-free.

TABLE 2.

Sample Number	Large	Medium	Small	Very Small	Trace	Minute Trace
1. Brown (clear)	Zr Si	—	—	Hf	Ca	Mg Ba
1a. (inclusions)	Zr Si	—	—	—	Fe Ca	Mg Ba
2. Brown (clear)	Zr Si	—	—	Hf	Ca	Mg Ba
2a. (inclusions)	Zr Si	—	—	—	Fe Ca	Mg Ba
3. Brown (clear)	Zr Si	—	—	Hf	Ca	Mg Ba
3a. (inclusions)	Zr Si	—	—	—	Fe Ca	Mg Ba
4. Blue	Zr Si	—	—	Hf	Ca	Mg Ba
5. Blue	Zr Si	—	—	Hf	Mg Ca	Ba
6. Blue	Zr Si	—	—	Hf	Mg Ca	Ba Ti
7. Blue	Zr Si	—	—	Hf	Mg Ca	Ba
8. Straw-yellow (clear)	Zr Si	—	—	Hf Ag	Mg Ca Na	Ba
9. Water-white (clear)	Zr Si	—	—	Hf	Mg Ca	Ba
10. Water-white (clear)	Zr Si	—	—	Hf	Mg Ca Ag	Ba
10a. Glaze	Zr Si Na	Ag	—	Al Fe Mg Ca	Li V	Ba

TABLE 2. (Continued)

Sample Number	Large	Medium	Small	Very Small	Trace	Minute Trace
10b. (inclusions)	Zr Si Fe	Al	—	Hf Ag	Mg Ca Na	Ba
11. Water-white (clear)	Zr Si	—	—	Hf	Ca	Ba
11a. (inclusions)	Zr Si Fe	—	—	—	Ca	Ba
12. Water-white (clear)	Zr Si	—	—	Hf	Ca	Ba
12a. (inclusions)	Zr Si	—	Fe	Hf	Ca Ti	Ba
13. Water-white (clear)	Zr Si	—	—	Hf	Ca	Mg Ba
13a. (inclusions)	Zr Si	—	Fe	Hf	Ca Mg Cu	Ba

The spectrographic technique has been previously described by one of us.⁹ The exposure time, however, was increased to 60 seconds. The long slit length of 7 mm. was found particularly advantageous in distinguishing spectral lines due to traces of impurities in the zircon from impurity lines in the electrodes. The results are given in Table 2.

DISCUSSION OF RESULTS

The refractive indices of the samples were checked by the use of high-refractive liquids,¹⁰ for the purpose of identifying the material examined. No significant differences were found in the refractive indices of any of the samples and the values were approximately $\omega = 1.928 \pm 0.005$ and $\epsilon = 1.980 \pm 0.005$.

By examination of Table 1, for density and the indices of refraction obtained, it appears that the material investigated was the *b*- or normal modification of zircon, as classified by Stevanovic, Eppler and Simon, since the density, which varied from 4.613 to 4.744 (averaging 4.684),

⁹ Kennard, T. G., *Am. Mineral.*, vol. 20, pp. 392-399, 1935.

¹⁰ West, C. D., *Am. Mineral.*, vol. 21, pp. 245-249, 1936.

as well as the refractive indices, agreed with their data.^{3,11} According to the classification of Bauer,¹² this is *alpha* zircon, which is the stable form as regards density and refraction changes due to the effects of heat.

Of especial interest is the similarity in composition of the various samples. It is noteworthy that no significant qualitative difference is shown in the spectra of the inclusion-free samples. Very small amounts of hafnium and traces of barium and calcium were found in all inclusion-free samples; in addition, very small amounts or traces of silver, magnesium, and sodium were found in one or more samples. With the exception of silver, the elements occurring in the samples are those generally found in zircons and have been previously reported.^{13,14} The silver, observed in the spectra of four samples, i.e., two zircons, the glaze, and certain black spots, is probably due to the chemicals used in heat-treating, since the silver content is very prominent in the sample of the glaze.

Thus it would appear that there is no marked difference in the chemical composition of these brown, blue and colorless varieties of the normal or *b*-modification of zircon. This is in accordance with the spectrographic findings of Wild,² who, however, reports that no impurities were found. This is rather astonishing inasmuch as hafnium has been reported to be ever present in zircon.¹⁵ As stated above, very small quantities of this element were found in all of the inclusion-free samples examined.

The blue and brown colors in the inclusion-free zircons are apparently not pigmental, but may be due to structure or colloids. Doelter, in particular, has favored the last-mentioned hypothesis for the coloration of many minerals, including zircon.⁵ The red spots, however, contained a considerable amount of iron, which could have been responsible, at least in part, for their color.

Thorium was not found, nor did the photoluminescence test, described by Papish and Hoag,¹⁶ show the presence of uranium. The absence of detectable quantities of lead agrees with these results.

SUMMARY

1. Brown, blue and colorless Siamese zircons have been examined spectrographically.
2. The inclusion-free portions of these three color-varieties showed no

¹¹ Simon, *N. Jahrb. Min., Abt. A., Beil-Bd.* **61**, pp. 165-226, 1930.

¹² Bauer, Max, *Edelsteinkunde*, 3rd Edition, revised by Karl Schlossmacher, Leipzig, 1932, p. 562.

¹³ Venable, Francis P., *Zirconium*, 1922, p. 98.

¹⁴ Doelter, C., *Handb. Mineralchemie*, **III**, Pt. 1, p. 133, 1918.

¹⁵ von Hevesy, *Chemical Analysis by X-Ray and Its Application*, 1932, p. 217.

¹⁶ Papish, Jacob and Hoag, L. E., *Proc. Nat. Acad. Sci.*, vol. **13**, pp. 726-728, 1927

differences in chemical composition, except for traces of magnesium, sodium and silver.

3. A very small amount of hafnium and traces of barium and calcium were found in all the inclusion-free samples; very small amounts or traces of silver, magnesium and sodium were found in one or more samples.

4. The black inclusions and red spots showed a marked difference in chemical composition from the inclusion-free material, being much richer in iron. Aluminum, copper and titanium were sometimes present.

5. The blue and brown colors in the inclusion-free zircons are not pigmental.

X-RAY DETERMINATION OF THE SILICA MINERALS IN SUBMICROSCOPIC INTERGROWTHS

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When tridymite and cristobalite are found in isolated grains or in relatively coarse intergrowths, they can easily be identified with the microscope. But, when they occur in submicroscopic intergrowths with feldspar, as often found in spherulites and the groundmass of lavas, they defy the ordinary means of identification; and whether a given rock is reported to contain cristobalite or tridymite may be largely a matter of personal opinion or prejudice. The purpose of this paper is to outline a method of determining the silica minerals when found in these intimate intergrowths, and to show the applicability of the method in analyzing the submicroscopic groundmass of lavas.

X-ray powder photographs¹ taken of quartz, tridymite, and cristobalite are shown in Fig. 1. Each gives a pattern that is sufficiently characteristic to distinguish it from the others. Consequently, the identification of an undetermined form of silica may be made merely by the direct comparison of its powder-picture with those of the known minerals. If the unknown mineral is part of an intergrowth, identification is less certain, for a more complex pattern results. However, each of the silica minerals gives one or more strong lines characteristically spaced, and may be recognized even when the picture is complicated by other lines. In this manner Kuno² was able to point out the presence of cristobalite in the groundmass of certain Japanese volcanics.

In order to make a graphic comparison of the powder photographs, photodensitometer records were made of them which are reproduced in Fig. 2. The line at the left of the figure marks the centers of the pictures, and each curve represents the indicated portion of the corresponding powder picture of Fig. 1. The higher the curve, the greater the blackening of the film, and thus the general downward trend of each indicates merely the tendency of the films to become less dense, due to scattered radiation, from the center outward. A sharp rise in a curve marks the position of a dark line on the film, and its height and width give respectively the density and width of the line. The density represented by a peak cannot easily be interpreted in absolute units because of the many variables that enter in, but the significant things are its distance from the center

¹ The x-ray powder photographs were taken with copper radiation. Inasmuch as they are for comparison, no filter was used, and the length of exposure was thereby reduced.

² Kuno, Hisashi, On silica minerals occurring in the groundmass of common Japanese volcanic rocks: *Bull. Earthquake Research Institute, Tokyo Imperial Univ.*, vol. 11, Part 2, 1933.

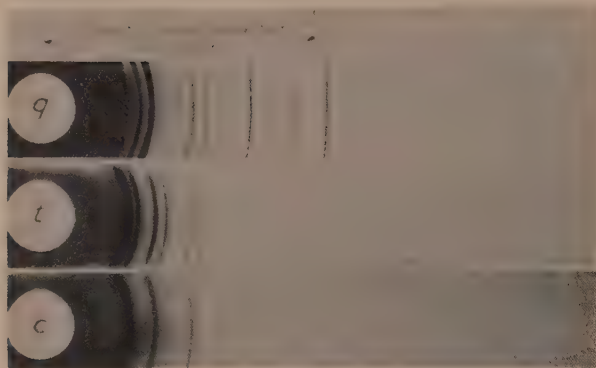


FIG. 1. X-ray powder photographs of the silica minerals taken with unfiltered copper radiation. *q*, Quartz; *t*, Tridymite; *c*, Cristobalite

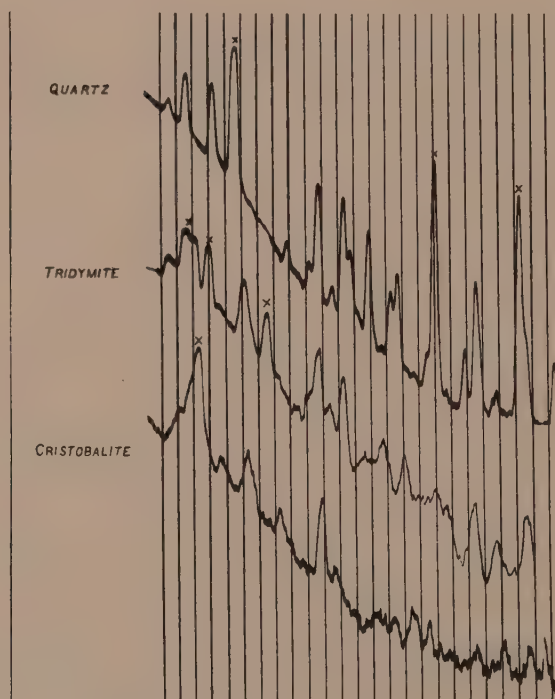


FIG. 2. Photodensitometer records of the x-ray powder photographs shown in Fig. 1.

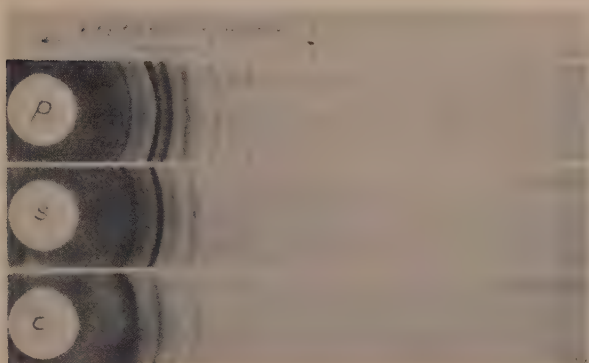


FIG. 3. X-ray powder photographs taken with unfiltered copper radiation. *p*, Perthite; *s*, Spherulite; *c*, Cristobalite.

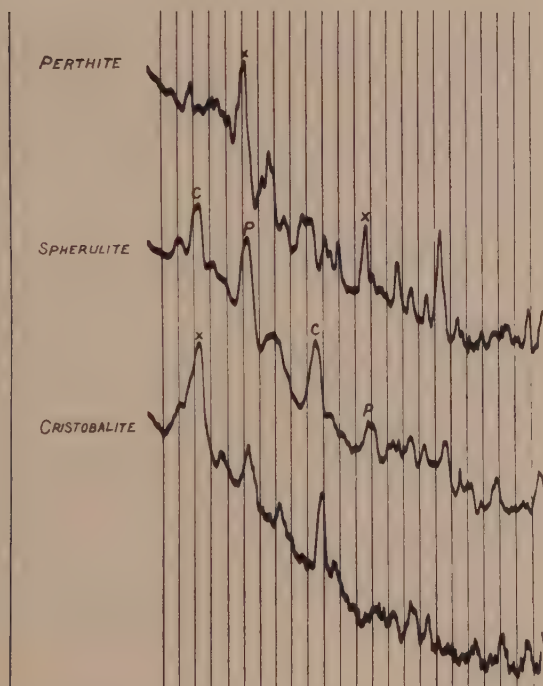


FIG. 4. Photodensitometer records of the x-ray powder photographs shown in Fig. 3.

and its relative height. The peaks of the curves in Fig. 2 marked with an x are considered diagnostic for each of the minerals.

X-ray powder photographs were taken of two spherulites found in New Mexican rhyolites and of the submicroscopic groundmass of two rhyolites from Colorado. In all four photographs the resulting pattern was identical, and is shown in Fig. 3(s).

It is generally agreed that, in addition to a silica mineral, feldspar of a composition approximating perthite is the chief constituent of these submicroscopic intergrowths. Accordingly, a powder photograph of perthite was made and is reproduced in Fig. 3(p) with those of the spherulite and cristobalite for comparison. The similarity of the spherulite and perthite powder pictures, as well as the corresponding photodensitometer records, Fig. 4, show that the assumed presence of feldspar is probably correct. A comparison of the photodensitometer curve of the spherulite with those of the silica minerals shows that it in no way corresponds to either quartz or tridymite, but a prominent peak in the spherulite curve falls exactly in the position of the diagnostic peak of cristobalite. The presence of cristobalite, therefore, may be reasonably inferred.

In Fig. 4, the major peaks on the spherulite curve that are believed to be caused by the presence of cristobalite are marked c , while those caused by the presence of perthite are marked p . In this manner all of the principal peaks on the spherulite curve are accounted for, and it may be concluded that feldspar and cristobalite are the dominant constituents.

ACKNOWLEDGMENTS

This study was undertaken at the suggestion of Professor E. S. Larsen with the hope of shedding light on the mineral composition of spherulites found in lavas in the San Juan Mountains of Colorado.³ The photodensitometer records were made at the U. S. Arsenal, Watertown, Mass., through the courtesy of Dr. H. H. Lester. The writer wishes to express his appreciation for help rendered in various ways in the preparation of this paper by Dr. Harry Berman and Dr. M. A. Peacock of the Department of Mineralogy of Harvard University.

³ Larsen, Esper S., and others. Petrologic results of a study of the minerals from the Tertiary volcanic rocks of the San Juan Region, Colorado: *Am. Mineral.*, vol. 21, pp. 679-701, 1936.

NOTES AND NEWS

ARE THERE 47 OR 48 SIMPLE FORMS POSSIBLE ON CRYSTALS?

A. K. BOLDYREV, *Fedorov Institute, Leningrad, U.S.S.R.*

In a recent paper A. F. Rogers¹ discusses different names of crystal forms now used by crystallographers and gives a list of the names he prefers. He pointed out also that 48 simple crystal-forms are possible.

In my paper on the nomenclature of simple forms adopted by the Fedorov Institute² it is shown that there are only 47 of these forms.

While it is quite clear that we can have different opinions of various form-names, concerning the number of possible simple forms there is only a single answer.

It is not difficult to establish that there is a divergence between A. F. Rogers, and our set of forms; here we deal again with a so-called "dome" and "sphenoid," that we consider a single form and call "dihedron."

In order to decide whether we have one or two forms in this case, it is necessary to give a precise definition of the term different "simple forms."

Definition: Two simple forms are different if they have a different number of faces, or if they differ in the shape, or mutual position of their faces.

If two forms have the same above mentioned properties they are not different, they belong to the same sort of polyhedrons, in spite of a difference in the symmetry operations by which they are obtained.

We follow this definition, and A. F. Rogers does also. He proves very clearly for instance (p. 839) that the $h k 0$ form of the rhombic syngony and the $h k l$ form of the monoclinic syngony are both rhombic prisms, and that the form consisting of two parallel faces in all symmetry classes must be called pinakoid.

In his list of simple forms (p. 842) he does not distinguish between the octahedron, derived in the polygyric central ($3G_2 \cdot 4G_3 \cdot 3P C$) class by means of P or C, and the octahedron derived in the polygyric axial ($3G_4 \cdot 4G_3 \cdot 6a_2$) class, by means of symmetry axes.

Also the forms $\{100\}$ both in the tetragyric primitive G_4 class and in tetragyroidic primitive G_{41} class, are named by Rogers tetragonal prisms although they are obtained by means of quite different symmetry operations.

Dipyramids, both in central (dipyramidal) and in axial (trapezohedral) classes of various syngonies, are also three excellent examples of this kind.

¹ Rogers, A. F., A tabulation of crystal forms and discussion of form-names: *Am. Mineral.*, vol. 20, pp. 838-851, 1935.

² Boldyrev, A. K., Die von Fedorov-Institut angenommene kristallographische Nomenklatur: *Zeit. Krist.*, vol. 62, pp. 145-150, 1925.

Only the use of both "dome" and "sphenoid" appears as an incompressible exception.

Fedorov pointed this out about 50 years ago and has replaced these two names by "hemiprism," which we have changed, according to G. V. Vulp, to "dihedron." We cannot use either one of the two former terms "dome," or "sphenoid," if we wish to avoid confusion, considering the old restricted sense of these words. Besides, it is well to remember that $\delta\omega\mu\alpha$ means *plane (not ridged) roof* like our monohedron (not dihedron).

To use these two names (as many crystallographers do) and to count 48 simple forms instead of 47 is not an opinion but a mistake, like the assertion that there are not 32 but 33 classes of crystal symmetry.

In addition to the above I will note that we agree entirely with A. F. Rogers' severe criticism of form-names that are based (1) on the position of the constituent faces with respect to the crystallographic axes, (2) on the mineral names, (3) on the merohedrism. Of course A. F. Rogers is quite right in declaring that only one method of form-naming, according to the number and shape of the faces, is adequate.

In relation to the list of simple form-names proposed by A. F. Rogers I can note that 32 of these names are identical with the names accepted by the Fedorov Institute, but 15 are different. Among the latter 5 belong to the lower and middle syngonies, and 10 others to the polygyric (cubic) syngony.

In the follow table I will give all 47 terms of the Fedorov Institute and 15 distinct names proposed by A. F. Rogers.

NAMES ACCEPTED BY THE FEDOROV INSTITUTE	NAMES PROPOSED BY A. F. ROGERS
1. Monohedron	= Pedion
2. Dihedron	= Sphenoid and Dome
3. Pinakoid	= Pinakoid
4. Rhombic Prism	= Rhombic Prism
5. Rhombic Pyramid	= Rhombic Pyramid
6. Rhombic Tetrahedron	= Rhombic Disphenoid
7. Rhombic Dipyr amid	= Rhombic Dipyr amid
8. Tetragonal Tetrahedron	= Tetragonal Disphenoid
9. Tetragonal Pyramid	= Tetragonal Pyramid
10. Tetragonal Prism	= Tetragonal Prism
11. Tetragonal Scalenohedron	= Tetragonal Scalenohedron
12. Tetragonal Trapezohedron	= Tetragonal Trapezohedron
13. Tetragonal Dipyr amid	= Tetragonal Dipyr amid
14. Ditetragonal Pyramid	= Ditetragonal Pyramid
15. Ditetragonal Prism	= Ditetragonal Prism
16. Ditetragonal Dipyr amid	= Ditetragonal Dipyr amid

NAMES ACCEPTED BY THE FEDOROV INSTITUTE		NAMES PROPOSED BY A. F. ROGERS
17. Trigonal Pyramid	=	Trigonal Pyramid
18. Trigonal Prism	=	Trigonal Prism
19. Trigonal Dipyrarnid	=	Trigonal Dipyrarnid*
20. Trigonal Trapezohedron	=	Trigonal Trapezohedron
21. Rhombohedron	=	Rhombohcdron
22. Ditrigonal Scalenohedron	=	Hexagonal Scalenohedron
23. Ditrigonal Prism	=	Ditrigonal Prism
24. Ditrigonal Pyramid	=	Ditrigonal Pyramid
25. Ditrigonal Dipyrarnid	=	Ditrigonal Dipyrarnid
26. Hexagonal Pyramid	=	Hexagonal Pyramid
27. Hexagonal Prism	=	Hexagonal Prism
28. Hexagonal Trapezohedron	=	Hexagonal Trapezohedron
29. Hexagonal Dipyrarnid	=	Hexagonal Dipyrarnid
30. Dihexagonal Pyramid	=	Dihexagonal Pyramid
31. Dihexagonal Prism	=	Dihexagonal Prism
32. Dihexagonal Dipyrarnid	=	Dihexagonal Dipyrarnid
33. <i>Tetrahedron</i>	=	Tetrahedron
34. Trigon-tritetrahedron	=	Tristetrahedron
35. Tetragon-tritetrahedron	=	Deltahedron
36. Pentagon-tritetrahedron	=	Tetartoid
37. Hexatetrahedron	=	Hexatetrahedron
38. <i>Octahedron</i>	=	Octahedron
39. Trigon-trioctahedron	=	Trisoctahedron
40. Tetragon-trioctahedron	=	Trapezohedron
41. Pentagon-trioctahedron	=	Gyroid
42. Hexoctahedron	=	Hexoctahedron
43. <i>Hexahedron</i> (cube)	=	Cube
44. Tetrahexahedron	=	Tetrahexahedron
45. Rhombo <i>dodecahedron</i>	=	Dohecahedron
46. Pentagondodecahedron	=	Pyritohedron
47. Didodecahedron	=	Diploid

* Belongs to hexagyrir (or hexagonal) syngony.

Concerning the 15 different names we must remark as follows:

1. Pedion is a new Greek word in the nomenclature. We can and must avoid it. The term "monohedron" agrees very well with other terms of the whole nomenclature.

2. The same can be said about "dihedron."

3. 4. As we do not accept the name "sphenoid" we must refuse "disphenoid" also, as a new Greek word.

5. Ditrigonal scalenohedron is better than hexagonal scalenohedron because this form belongs to the trigonal, not to the hexagonal, syngony.

As to the forms of polygyric syngony we will make the following remarks:

(a) Many terms used by A. F. Rogers do not agree with the accepted principal: to name the forms according to the number and shape of the faces. Such are: tetartoid, gyroïd, (cube), pyritohedron, diploid.

(b) The current form-names in cubic syngony are based on very diverse principles. Therefore we are obliged to use here new names in spite of the inconvenience of such a method.

(c) Our terms are selected according to a strict plan. As is shown in the previous table, 15 simple forms of the polygyric syngony may be classified into four "families": related to the tetrahedron, octahedron, hexahedron and the dodecahedron. All our form-names of each "family" are built up uniformly.

Our experience in teaching has shown that this nomenclature is very easily grasped by students: after hearing the names of the forms belonging to the tetrahedral "family" they derive themselves all other names, almost without help from the teacher.

(d) One defect of our terms is that they are longer than many others. But this defect redeems itself by their positive qualities mentioned above.

The only adequate method of *naming the symmetry classes* is the naming according to the symmetry elements and not according to any one form. For details see our paper on this subject.³

³ А. К. Боллырев и В. В. Доливо-Добровольский. Классификация, номенклатура и символика 32 видов симметрии кристаллов (Classification, nomenclature and symbolization of 32 symmetry classes of crystals. (Russian with German "Zusammenfassung"). (Записки Ленинградского Горного Института УИИ. 1934. 145-159.